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Phase II Geologic Characterization Data Acquisition

Task 2 Additional Shallow, High-Resolution Seismic Reflection Profiling on Indiana Street

Final Report

U.S. Department of Energy
Rocky Flats Plant
Golden, Colorado

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EG&G Rocky Flats, Incorporated

PHASE II GEOLOGIC CHARACTERIZATION DATA ACQUISITION

TASK 2
ADDITIONAL SHALLOW HIGH-RESOLUTION SEISMIC REFLECTION PROFILING ON INDIANA STREET

Final Report
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Prepared by:

THE EBASCO TEAM
Ebasco Services Incorporated
Dames & Moore
Science Applications International Corporation
S.M. Stoller Corporation

Prepared for:

EG&G ROCKY FLATS, INC.
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EXECUTIVE SUMMARY

EG&G Rocky Flats, Inc. is performing remedial investigations, feasibility studies, and remedial/corrective action projects at the Rocky Flats Plant (RFP) under the U.S. Department of Energy's Environmental Restoration Program. These investigations have identified the potential for soil, surface water, and groundwater contamination. Stratigraphic and structural features in the bedrock, such as channel deposition or faults, may influence the potential movement of groundwater at RFP. The stratigraphy underlying the plant site displays the typical complexities of fluvial-deltaic sedimentation. Characterizing the stratigraphy by conventional methods alone, such as drilling, would not be cost effective.

To assist in characterizing the stratigraphy and in identifying possible structural features at RFP, a shallow, high-resolution (HR) seismic reflection program was developed and implemented. HR seismic is a noninvasive technique that can provide valuable information about the characteristics of the subsurface both between boreholes and in horizons deeper than those penetrated by boreholes. The technique can also be used to define the geometries of lithofacies and structures that may have an effect on groundwater flow. By using HR seismic data, the number of boreholes necessary to adequately characterize an area can be minimized, thereby reducing investigation costs. HR seismic data, when integrated with borehole data, provide a detailed subsurface profile from 20 to 500 feet in depth that will allow the following:

- Identification of fluvial deposits, geologic unit boundaries, apparent dip of geologic units, and lateral discontinuities caused by lithologic changes or faulting that may influence groundwater migration

- Estimation of depths to structural and stratigraphic targets prior to drilling

- Optimization of borehole and groundwater monitoring well locations

The shallow HR seismic program was implemented along Indiana Street, the eastern boundary of RFP, to identify stratigraphic and structural features that could be influencing the migration of groundwater off the plant site.

Using HR seismic data, several anomalies that may correspond to channel deposits within the Laramie Formation were identified along Indiana Street. These anomalies most likely define an area where a stream or a series of small streams meandered back and forth over time, depositing sediments. The channel deposits may be potential flow paths for groundwater to migrate off the RFP property. Whether the channel anomalies along Indiana Street are hydrologically connected to any potential contaminant sources on RFP is not known since the seismic program is by nature two dimensional.

Three possible reverse faults were identified on one of the Indiana Street seismic profiles. The faults show up to 40 feet of displacement on the Laramie/Fox Hills horizon. Although the apparent motion of these fault blocks is up to the north, the orientation of the fault planes cannot be determined since the seismic program is by nature two dimensional. Moreover, it cannot be determined whether the faults extend to the top of bedrock or whether they act as barriers or conduits to groundwater flow.

Small anticlines and synclines were also identified on the Indiana Street seismic profiles. These structures are most apparent on the Laramie/Fox Hills reflectors.

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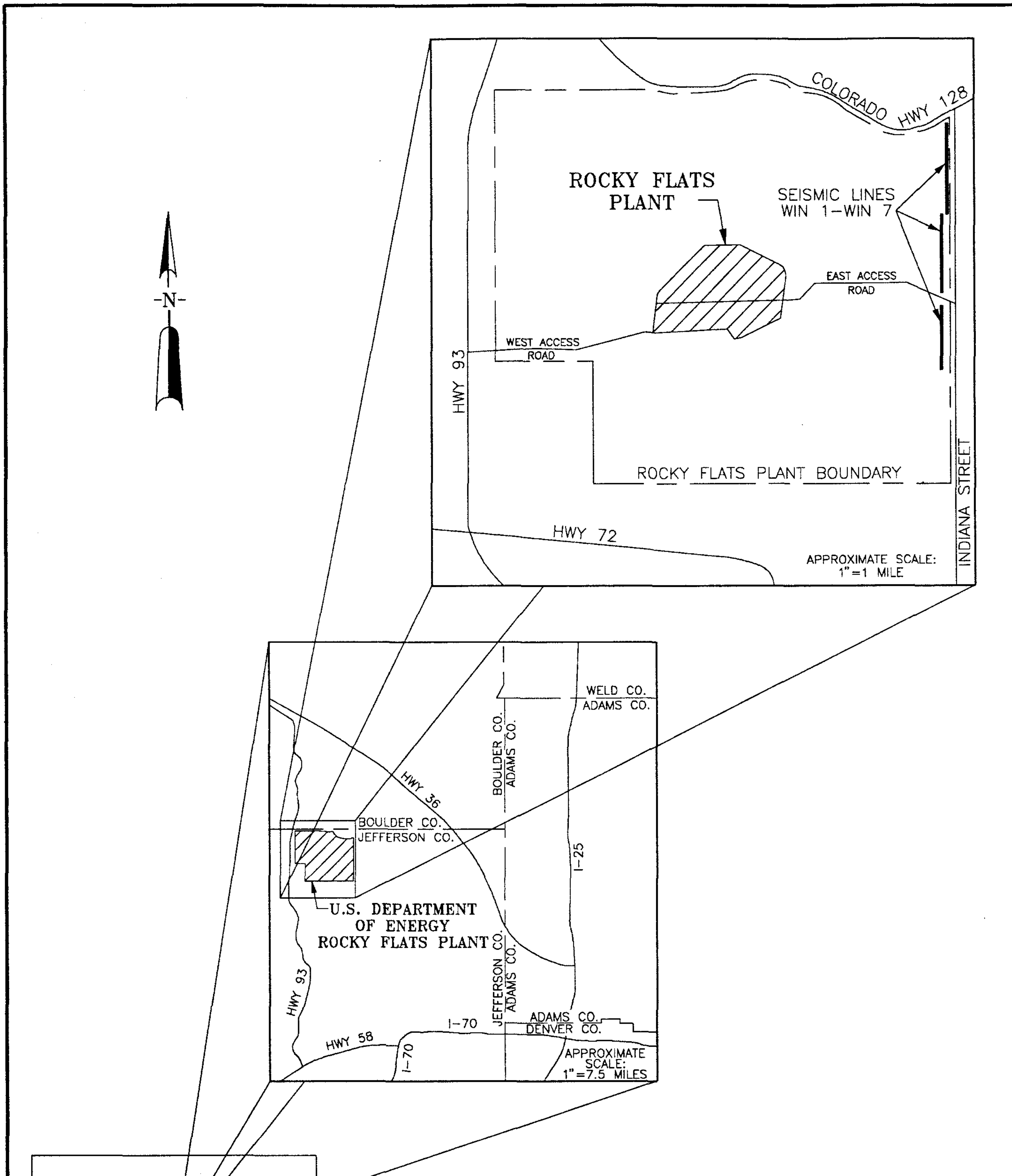
ACRONYMS AND ABBREVIATIONS

CDP	common depth point
CSM	Colorado School of Mines
DOE	U.S. Department of Energy
db	decibels
EG&G	EG&G Rocky Flats, Inc.
ft/sec	feet per second
ft	foot
HR	high-resolution
Hz	hertz
ms	millisecond
OU2	Operable Unit 2
RFP	Rocky Flats Plant
SEG	Society of Exploration Geophysicists
TD	total depth
VSP	vertical seismic profiles

1.0 INTRODUCTION

Rocky Flats Plant (RFP) is a U.S. Department of Energy (DOE) nuclear weapons facility managed by EG&G Rocky Flats, Inc. (EG&G). RFP is located approximately 11 miles northwest of Denver, Colorado, in northern Jefferson County (Figure 1-1). EG&G is performing remedial investigations, feasibility studies, and remedial/corrective action projects at RFP under the DOE Environmental Restoration Program. Previous remedial investigations conducted at RFP have identified the potential for soil, surface water, and groundwater contamination. Stratigraphic and structural features in the bedrock such as channel sandstones or faults may influence the potential movement of groundwater at RFP. The stratigraphy underlying the plant site displays the complexities typical of fluvial-deltaic type of sedimentation. Characterizing the stratigraphy by conventional methods alone, such as drilling, would not be cost effective. By using shallow high-resolution (HR) seismic data, the number of boreholes necessary to adequately characterize an area, and consequently the volume of investigation-derived wastes can be minimized, thereby reducing investigation costs.

Several previous studies have included seismic reflection data acquired on RFP property. Figure 1-2 shows the location of all the available seismic data at RFP. In late 1975 and early 1976, Rockwell International arranged for Colorado School of Mines (CSM) to acquire approximately 13 miles of reflection data on 11 seismic lines in the vicinity of RFP and the Eggleston Reservoir (Davis 1976). Most of these data are no longer available. In 1989, all of the available CSM raw field data, which consisted of 3 miles of data, i.e., lines CSM-5 and CSM-6, were reprocessed to reveal possible ramp thrusts in the Pierre Shale (ASI 1989). In 1992, one 11-mile seismic line (line RFD-1) that originated 2 miles up Coal Creek Canyon, crossed RFP, and terminated at the Great Western Reservoir (EG&G 1993) was acquired. Each of these studies focused on the structural trends of horizons below the Pierre Shale and so do not directly relate to shallow HR seismic investigations.



U.S. DEPARTMENT OF ENERGY
Rocky Flats Plant, Golden, Colorado

General Location of Rocky Flats Plant

Figure 1-1

February 1993

Shallow HR seismic investigations have been conducted at RFP to characterize the plant site hydrology and geology. Approximately 2.5 miles of shallow HR seismic data were acquired on RFP property in the West Spray Field (line WSF-1), Operable Unit 2 (OU2) (lines MPS-1 through MPS-14), and along Indiana Street (lines WIN-1 through WIN-3) between 1989 and 1992 to aid in the hydrologic characterization of RFP (Rockwell 1989; EG&G 1991, 1992a). This shallow HR seismic program was designed to characterize the subsurface between depths of 50 to 300 feet. These data were used to identify channel deposition and geologic structures that may influence groundwater flow.

As part of the RFP Phase II Geologic Characterization, a total of 8,750 linear feet (ft) of shallow HR seismic reflection data were acquired on the eastern boundary of RFP along Indiana Street. Initially, 2,400 linear ft of data were acquired in June and July 1990 to identify pathways that could possibly allow groundwater to migrate off the plant site (lines WIN-1 through WIN-3) (EG&G 1992a). An additional 6,350 linear ft of HR seismic reflection data were acquired in May and June 1992 to connect and extend seismic coverage along Indiana Street (lines WIN-4 through WIN-7) (Figure 1-3). This report presents the interpretation and results of all the Indiana Street HR seismic reflection data. To interpret the stratigraphy and structure along Indiana Street, the seismic data were integrated with borehole lithologic logs, geophysical logs, vertical seismic profiles (VSPs), and recent surface geologic mapping.

This report will be used by EG&G as a decision tool to perform the following:

- Map geologic structure and stratigraphy
- Provide hydrogeologic data for the design of efficient monitoring systems
- Optimize boring and monitoring well placement
- Select hydrostratigraphic units for future studies, such as aquifer tests and water quality tests

2.0 GEOLOGIC SETTING AT ROCKY FLATS PLANT

RFP is located along the western edge of the Denver Basin. It is bounded on the west by the Colorado Front Range and is underlain by more than 10,000 feet of Pennsylvanian to Upper Cretaceous sedimentary rocks of the Denver Basin that have been locally folded and faulted. The sedimentary bedrock is unconformably overlain by unconsolidated Quaternary alluvial sands and gravels.

The HR seismic reflection survey was able to provide information about the subsurface from the unconsolidated alluvial material to the Upper Cretaceous Pierre Shale (approximately 600 to 700 feet below ground surface). Described below are the lithologic units, beginning with the Pierre Shale at depth and continuing to the alluvial deposits of the ground surface. A generalized stratigraphic column of the geologic section at RFP can be found in Figure 2-1; a more detailed description of the geology older than the Upper Cretaceous can be found in the Phase II Geologic Characterization report (EG&G 1992b).

The Pierre Shale consists of approximately 7,500 ft of clayey marine shale. The lower portion of the formation is composed of massive to thin-bedded, dark gray to weathering dusty yellow, silty bentonitic claystone, with a few very thin, moderate brown, noncalcareous siltstone beds (EG&G 1992b). The upper portion of the formation is composed of thin-bedded to massive, dark gray to olive-gray, silty, bentonitic shale, with a few limestone concretions and thin, poorly cemented sandstone beds (Wells 1967).

The Fox Hills Sandstone conformably overlies the Pierre Shale and is approximately 90 to 140 ft thick (EG&G 1992b). The lower part of the Fox Hills Sandstone is composed of laminated to thin-bedded, very fine to fine-grained, light olive-gray to yellowish gray silty sandstone that weathers light olive-brown to moderate yellowish brown. Near its base, the Fox Hills Sandstone consists of an interbedded sequence of sandy shales and thin sandstones. Small variations in thickness are attributed to the gradational nature of the contact between the Fox Hills Sandstone and the Pierre Shale. The upper part of the Fox Hills Sandstone is

Age	Formation	Thickness (feet)	Description
Upper Cretaceous	Arapahoe Fm.	0'-120'	**Claystone, sandy claystone, and clayey sandstone, medium to coarse sandstone and chert pebble conglomerate locally at base -** gray to yellowish orange
Upper Cretaceous	Laramie Formation	600'-800'	**Sandstone and claystones -** gray, fine- to medium-grained; thin coal beds in lower part; ironstone nodules
Upper Cretaceous	Fox Hills Sandstone	90'-140'	**Sandstone -** Light olive gray to yellowish brown fine- to medium-grained, cross-bedded and laminated silty sandstone and shale at base
Upper Cretaceous	Pierre Shale	6000'-8000'	**Shale -** dark gray, silty, bentonitic; few thin, silty sandstones
Upper Cretaceous	Niobrara Formation	350'	**Shale -** olive gray to dusky yellow, very calcareous, thin bentonite, gypsum, and *fossiliferous limestone beds* **Limestone -** light gray, dense, fossiliferous
Upper Cretaceous	Benton Shale	450'-500'	**Limestone -** yellowish gray, sandy, fossiliferous **Shale -** dark gray with bentonite streaks, thin limestones in middle part **Shale -** dark gray to black, brittle, silty
Lower Cretaceous	Dakota Group: South Platte Formation	200'-350'	**Sandstone -** light gray, fine- to medium-grained, cross-bedded, dark gray claystone in middle part
Lower Cretaceous	Dakota Group: Lytle Formation	30'-100'	**Sandstone -** light gray to tan, fine- to coarse-grained, locally conglomeratic, frequent red and green siltstone interbeds
Jurassic	Morrison Formation	250'	**Shale and siltstone -** gray to greenish-gray to red, thin limestones in middle part; lenticular sandstones in upper and lower part
Jurassic	Ralston Creek Formation	110'	**Siltstone and silty shale -** light gray siltstone and light red silty shale; calcareous; chert nodules and beds
Triassic / Permian	Lykins Formation	450'	**Siltstone and claystone -** red with two laminated limestones in lower part
Permian	Lyons Sandstone	150'	**Sandstone -** pinkish-gray, fine- to medium-grained, cross-bedded; conglomeratic lenses frequent
Pennsylvanian	Fountain Formation	800'	**Sandstone and conglomerate -** red, fine- to coarse-grained, arkosic, thin, lenticular red siltstones frequent throughout
Precambrian			Gneiss, schist, and small granitic intrusions

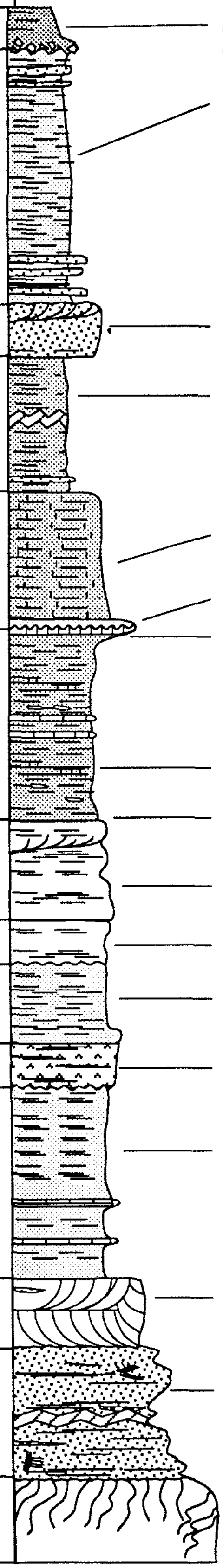


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Figure 2-1

Generalized Stratigraphic Section for the Rocky Flats Plant Vicinity

After LeRoy and Weimer 1971

composed of thick-bedded to massive, planar-laminated to cross-bedded, very fine to medium-grained, light olive-gray to yellowish gray silty sandstone that weathers white to dark yellowish orange. The Fox Hills Sandstone is unconformably overlain by the basal sandstone facies of the Laramie Formation.

The Laramie Formation is comprised of sandstones, siltstones, claystones, and coals deposited in fluvial-deltaic and lacustrine environments (Weimer 1973). The Laramie Formation is approximately 600 to 800 ft thick (EG&G 1992b) and is informally subdivided into a lower, predominantly sandstone unit and an upper, predominantly claystone unit. The base of the Laramie Formation is placed at the base of a thin, blocky grayish brown, carbonaceous claystone. Above this claystone is a series of thin- to thick-bedded, very fine to fine-grained yellowish gray sandstones. The sandstones are interbedded with blocky, brownish gray claystones, grayish black carbonaceous shales, and black coals. The upper Laramie is generally distinguished from the lower Laramie where the formation becomes dominantly composed of olive-gray and yellowish orange claystones with no thick sandstone beds (EG&G 1992b). Both units are exposed in outcrops or are present in cores from monitoring wells and boreholes west of RFP (Rockwell 1987).

The lower Laramie sandstones and Fox Hills Sandstone collectively comprise the Laramie/Fox Hills Aquifer and are a major source of water in some parts of the Denver Basin (Romero 1976).

The Arapahoe Formation, a 60 to 100-ft-thick fluvial deposit, consists of interbedded conglomerates, sandstones, siltstones, and claystones. The sandstones are lenticular and rarely exceed 5 to 8 ft in thickness with a lateral extent of tens of feet. The sandstones are quartzose, fine to coarse-grained, locally conglomeratic, and commonly silty and clayey. In Jefferson and Boulder counties, the lower Arapahoe has been described as containing a conspicuous conglomerate, one of the most recognizable units in the Golden area (Malde 1955; Weimer 1973; EG&G 1992b). This conglomerate contains fragments derived from the crystalline complex farther west and from local sedimentary rocks. The conglomerate serves locally as a stratigraphic marker separating the Arapahoe and Laramie Formations (Weimer 1973). The Arapahoe Aquifer consists of the basal conglomerate and other porous lower Arapahoe sandstones (Romero 1976).

The conglomerate base of the Arapahoe Formation has been mapped in the subsurface (Romero 1976) and in outcrops on and near RFP. A recent investigation at RFP (EG&G 1992b) suggested that the stratigraphic equivalent to the basal Arapahoe conglomerate is present at the surface in certain areas at RFP. The stratigraphic equivalent of the Arapahoe conglomerate is a medium frosted-grained sandstone (EG&G 1992b).

The alluvial material found on the east side of RFP in the area of Indiana Street consists of Valley Fill alluvium and colluvium. The Valley Fill alluvium, which occupies the active stream channels, is composed of light brown to brownish grey humic clay, silt, sand, and pebbly sand with silty and cobbly gravel lenses. Colluvium, or slope wash, occurs on the valley sides above active channels.

2.1 BEDROCK DEPOSITIONAL MODEL

As evidenced in boreholes at RFP, the predominant lithologies that comprise the upper 200 ft of Cretaceous bedrock are claystones, siltstones, and fine-grained sandstones. According to Davis and Weimer (1976), these lithologies indicate a relatively low-energy deltaic depositional environment. Sedimentation in deltaic systems results in widespread, thick deposits of claystones and siltstones of low permeability, along with narrow, thin, and localized deposits of more permeable channel sandstones.

A conceptual model of the depositional environment at RFP suggests the presence of low-gradient, low-energy streams, with banks consisting of cohesive fine-grained sediments derived from suspended load. These streams are superimposed upon a more extensive deltaic system (Figures 2-2 and 2-3). This postulated deltaic depositional environment is supported

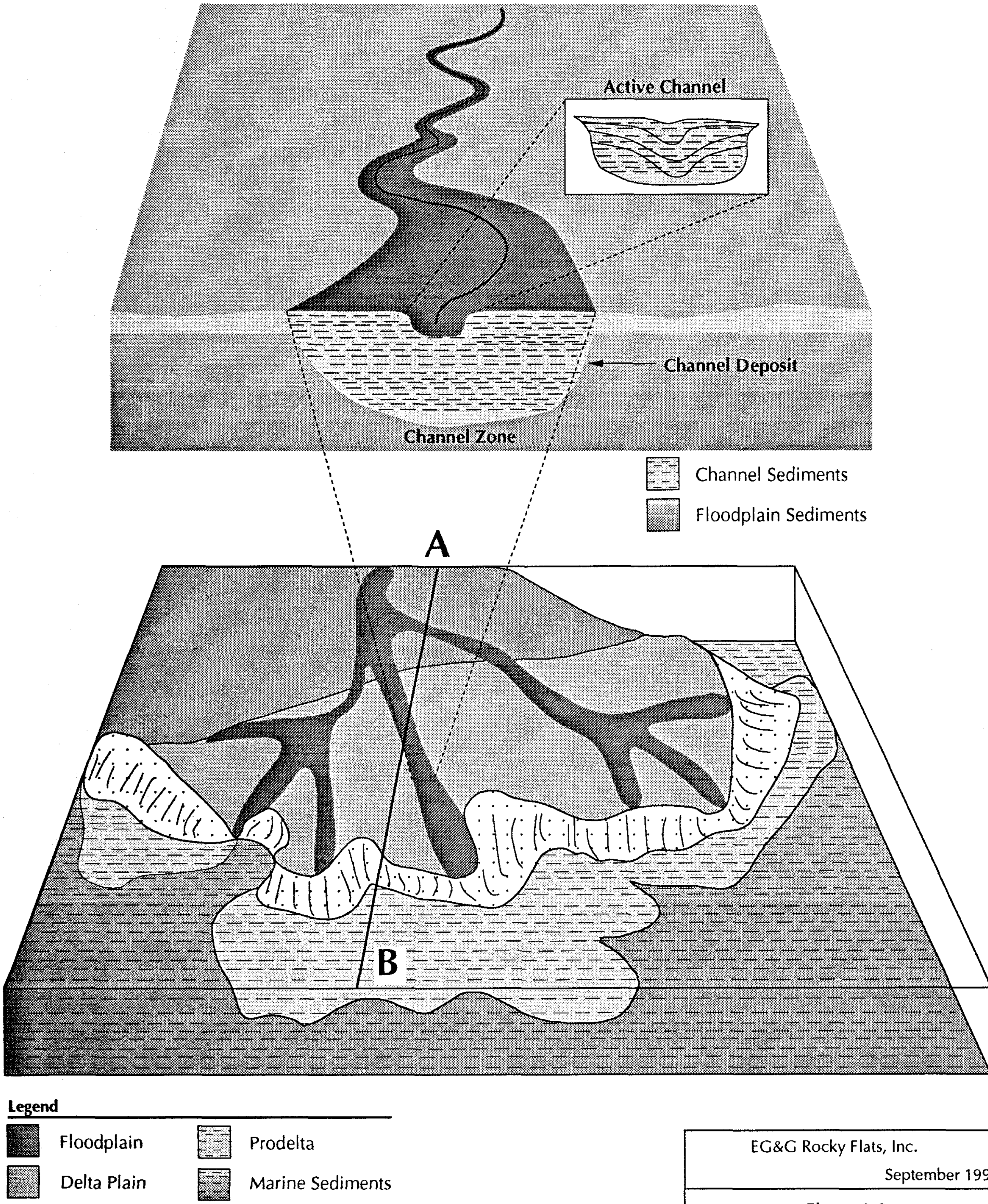

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Figure 2-2
UPPER CRETACEOUS DELTAIC DEPOSITIONAL MODEL

After Elliott 1978

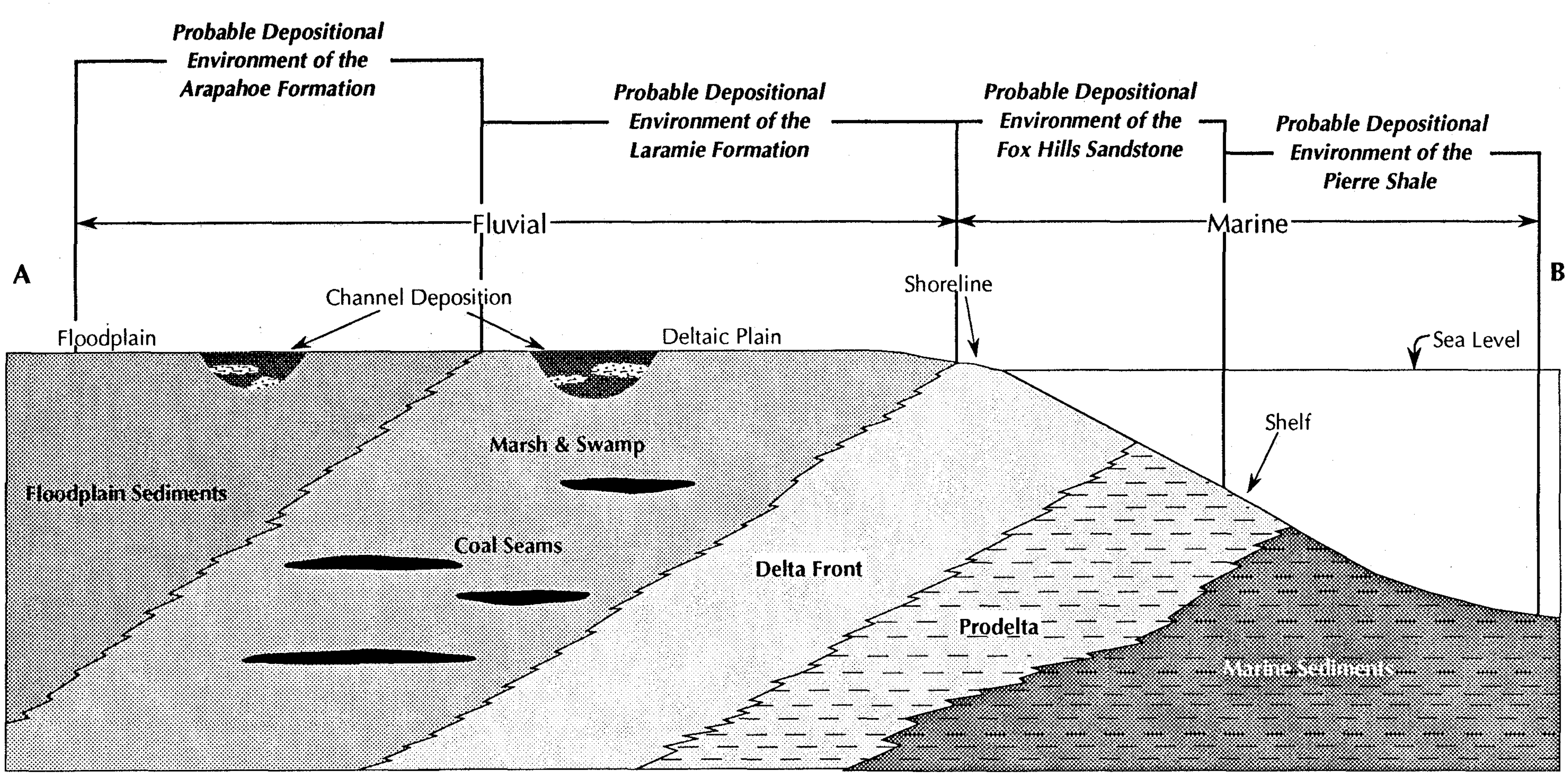

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FIGURE 2-3

UPPER CRETACEOUS DELTAIC DEPOSITIONAL MODEL, CROSS-SECTION A-B

After Weimer 1973

by evidence gathered during previous shallow HR seismic reflection programs (EG&G 1992a, 1991; Rockwell 1989). The Task 3 shallow HR seismic reflection program identified anomalous zones that define the limits of channel deposition (EG&G 1991). These anomalous zones do not represent one sandstone-filled channel, but rather a series of channel-type depositional sequences consisting of claystones, siltstones, and sandstones. On the deltaic plain, a stream or series of streams meander, within certain limits, for a period of time. These limits can be controlled by subtle structures or by subsidence, which creates topographic lows where streams would preferentially flow. Within the limits of channel deposition, several channels will deposit sediments over time. Sediments within the channel will range in size from clay to sand. Relatively more sandstones will be deposited in the channel than on the rest of the deltaic plain. Although the channel sandstones may constitute only a small portion of the total channel deposit, their permeabilities and hydraulic conductivities will potentially be greater than the sediments deposited outside of the channel. Consequently, the channel deposits may act as potential conduits for groundwater migration. Therefore, it is important to delineate channel deposits under RFP. HR seismic reflection data were acquired to map these channel deposits in the Laramie Formation.

2.2 GEOLOGICAL STRUCTURES AT ROCKY FLATS PLANT

RFP is known to be in proximity to geologic faults, and recent investigations have shown that faults exist under the plant property (EG&G 1990, EG&G 1993). Seismic data acquired by CSM was reprocessed and reinterpreted as part of the Phase I Geologic Characterization of RFP (EG&G 1990). The reinterpretation of this data indicates thrust faults under the plant site in the Pierre Shale ramp from west to east. The interpretation of line RFD-1 presented in the deep seismic report (EG&G 1993) indicates small, high-angle imbricate thrust faults under the RFP property. These faults originate from a sole thrust fault parallel to bedding at the base of the Pierre Shale. The high-angle imbricate faults ramp from approximately 8,000 ft below ground surface and appear to terminate or return to bedding planes 3,000 ft to 2,000 ft below ground surface. Total vertical displacement along these faults is approximately 150 ft.

Because of the two-dimensional nature of the seismic line, the orientation of these faults is unknown.

Kittleson (1992) has speculated that northeast-southwest-trending faults in the Boulder-Weld Fault Zone (north of RFP) project under the plant site. The faults in the Boulder-Weld Fault Zone are mapped in the top of the Pierre Shale, Fox Hills Sandstone, and Laramie Formation. Although faults on line RFD-1 are interpreted in the lower to upper Pierre Shale, the displacements are similar to the Boulder-Weld Fault Zone (approximately 150 to 200 ft). It is not known if the two sets of faults have similar orientations or are related to similar structural events.

Finally, the Phase II Geologic Characterization report (EG&G 1992b) suggests that faulting is a possible mechanism to explain approximately 100 ft of thinning in the Laramie Formation on RFP property between OU2 and Indiana Street.

One of the objectives of the shallow HR seismic program along Indiana Street was to identify any potential faulting on the Eastern Boundary of RFP. The presence of faults at RFP is of concern because faults can provide potential conduits or barriers to the flow of groundwater laterally off the plant site or vertically into deeper formations.

3.0 SEISMIC REFLECTION PROGRAM

3.1 INTRODUCTION

Seismic reflection profiling consists of producing an acoustic wave that propagates through the earth and recording the waves that are reflected back to the surface from subsurface rock layers and fault planes. The reflected acoustic waves are detected by geophones and recorded on a seismograph. The shallow HR seismic method uses a low energy source, high-frequency geophones, and a short geophone station interval (less than 20 ft) that allows for the mapping of reflection from beds that are only a few feet thick. Combined with the common depth point (CDP) method of seismic reflection profiling, lithologic beds and structural features (e.g., folds and faults) can be identified and mapped. Appendix I discusses seismic reflection techniques, including the CDP method.

All field procedures used during data acquisition of the additional shallow seismic along Indiana Street were performed in accordance to the work plan generated specifically for this seismic reflection program (EG&G 1992c), and all equipment used for this seismic reflection program was as specified in the work plan, with no deviations.

3.2 ACQUISITION OF INDIANA STREET DATA

HR seismic reflection data from three 800-ft lines were previously collected on the east boundary of RFP along Indiana Street in June and July 1990 (EG&G 1992a). An additional 6,350 ft of HR seismic reflection data were collected in May and June 1992 that connected and extended the original three lines.

The same seismic parameters tested and proven successful in previous RFP HR seismic programs (Rockwell 1989; EG&G 1991, 1992a) were used to acquire the additional data along the Indiana Street lines. Table 3-1 shows the Indiana Street data acquisition parameters. At the beginning of data acquisition, shot records were carefully examined to ensure that the necessary resolution was being obtained. Geophones were spaced 2 ft apart and shotpoints 4 ft apart, resulting in 24-fold data. An unbalanced split-spread geophone geometry was used because it emphasizes and improves the resolution at the depths of interest (50 to 300 ft). With an unbalanced split-spread geophone geometry, the seismic source is detonated between one end of the geophone spread and its center, in contrast to a balanced split-spread geometry, in which the source is detonated at the center of the geophone spread.

3.3 EQUIPMENT USED IN DATA ACQUISITION

A Geometrics ES-2420 digital reflection seismograph was used for the RFP shallow HR seismic reflection survey. This seismograph has the capability to sample seismic data every

Table 3-1 Indiana Street Data Acquisition Parameters

Geophone Station Spacing	2 feet
Source Spacing	4 feet
Geophones Per Station	1
Geophone Frequency	100 Hertz
Spread Length	190 feet
Far Offset	142 feet
Cable Geometry	unbalanced split spread
Number of Recording Channels	96
Sample Rate	0.25 milliseconds
Maximum Record Length	500 milliseconds
Low-Cut Filter	100 Hertz
Alias Filter	720 Hertz
Filter Slope	18 and 52 decibels/octave
Common Depth Point Fold	24

0.25 millisecond (ms) on as many as 512 recording channels. A 0.25-ms sample rate and 96 channels were used for this project.

Custom geophones and cables were used during the Indiana Street HR seismic reflection survey. The cables were 120 ft long, and the geophone connections (takeouts) were set 2 ft apart. To achieve the desired geologic resolution, 100-Hertz (Hz) geophones, which are able to record high frequency energy more effectively than lower frequency geophones, were used. 100 Hz geophones also reduce the low frequency noise associated with the source generated ground roll.

Based on the success of previous shallow HR seismic work done in OU2 at RFP (Rockwell 1989; EG&G 1991), an industrial 8-gauge blank cartridge with a 250- to 300-grain charge was the energy source was selected and used during the Indiana Street survey. Electric cartridges were preferred because the detonation system has a safer and more reliable activation mechanism. Each cartridge was detonated in a hole drilled 2 to 5 ft deep and backfilled with sand.

All seismic reflection data were recorded on a 9-track computer tape in Society of Exploration Geophysicists (SEG) D format (SEG 1980). Appendix II describes in detail the equipment used for shallow HR seismic reflection data acquisition. Field tapes and survey data were sent to a seismic data processing center for processing.

3.4 DATA PROCESSING

The basic objective of all seismic data processing is to convert the data recorded in the field into a form that can be used for geological interpretation. An important step in data processing is to eliminate or reduce all noise (energy not associated with primary reflections, and especially energy that interferes with primary reflections). This step in data processing is known as filtering. Closely associated with filtering is signal enhancement, which involves increasing the frequency bandwidth and amplitudes of the primary reflections. Another important step in data processing is to resolve near-surface velocity changes that may affect the stacking of the data. This was done by using a refraction statics program that first determines the lateral and vertical velocity variations within the alluvium and upper bedrock, and then compensates for the effects of these variations on the data.

The processing sequence (Figure 3-1) included a variety of programs that are normally applied to CDP seismic data. After data acquisition and initial data analysis, the exact processing sequence was designed. During various steps in the processing sequence, the processing geophysicist consulted with the project geophysicist to ensure optimum data quality. Appendix III provides a detailed description of the data processing programs used. The end result of the data processing operations was the generation of a two-dimensional seismic profile that represents a geologic cross-section of the subsurface.

4.0 DATA INTERPRETATION

The goal of seismic interpretation is to relate seismic events to geologic features. Certain geologic features may produce distinctive seismic reflections. For example, large density and/or velocity contrasts in lithology would result in high-amplitude reflections, while smaller contrasts would result in low-amplitude reflections. A high degree of interbedding could result in an increased number of reflections for that sedimentary sequence.

The seismic profiles produced from the Indiana Street data were used to identify geometric anomalies that include converging and diverging reflections and convex downward reflections. The seismic anomalies may represent channel depositional features such as interbedding, channel edge pinchouts, or scouring, or they may represent ancient geomorphic features that control channel locations.

The complex trace attributes displayed in this section for lines WIN-4 through WIN-7 are instantaneous frequency and instantaneous phase. The instantaneous frequency displays show the frequency content of the data, while instantaneous phase displays enhance low-amplitude,

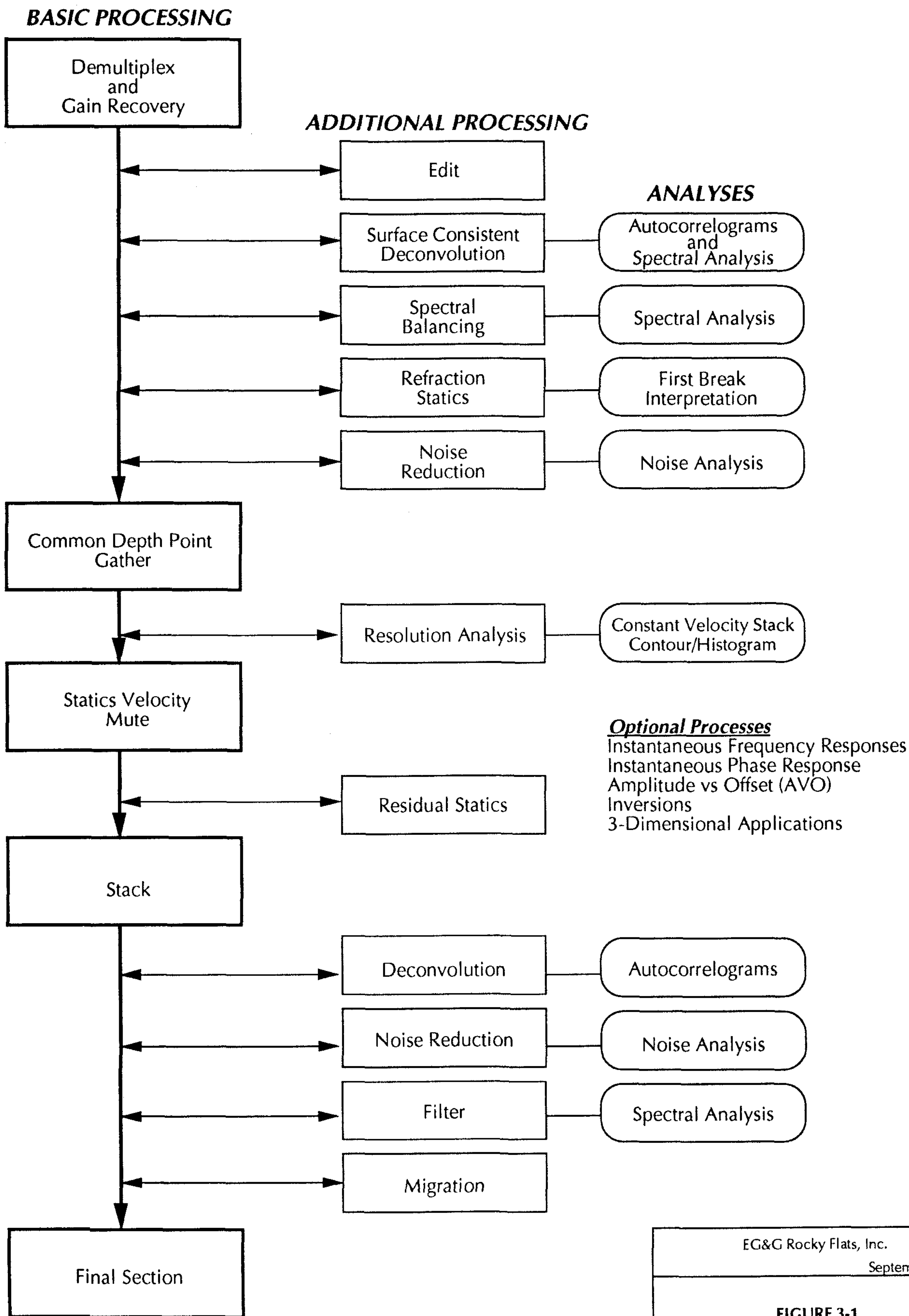

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FIGURE 3-1

SEISMIC DATA PROCESSING ROUTINES

After Sheriff, 1984

coherent events. Tanner and Sheriff (1977) have shown that changes in lithology are indicated by changes in the instantaneous frequency response in certain cases. The instantaneous frequency plots generated from the OU2 seismic lines showed, in some cases, a relationship between channel deposits and high frequencies (EG&G 1991). The relationship between the instantaneous frequency and lithology is empirical and the mechanism by which this relationship occurs is not entirely known. However, along Indiana Street, this relationship does not appear to exist since the seismic data do not exhibit high frequencies where sands are known (from borehole data) to exist. The instantaneous phase displays were used to help identify structural features, such as faults, and stratigraphic features, such as converging and diverging reflections.

Appendix III presents a detailed discussion of complex attribute analysis. VSP data, presented in Appendix IV, were used to determine seismic velocities that were used to convert seismic times of events to depth. The VSP data were also used to identify and correlate seismic reflections to lithology.

This report provides an interpretation of lines WIN-4 through WIN-7, using the enhanced filtered, final-stack seismic profiles; complex trace attributes plots; borehole data;, and VSPs. The folder accompanying this report provides interpreted seismic profiles for lines WIN-1 through WIN-7. The channel deposit anomalies on lines WIN-1, 2, and 3 were updated using the most recent borehole data. A detailed interpretation of Indiana Street seismic lines WIN-1, 2, and 3; complex trace attributes (instantaneous phase and frequency) plots; and interpreted migrated seismic sections was submitted to EG&G in a final seismic report in February 1992 (EG&G 1992a).

Ten boreholes were available for correlation to the Indiana Street seismic data (Figure 1-2). Boreholes 41691, 44792, 4-86, and 40391 are located at the midpoint of line WIN-1, boreholes B217289, 0386, and 40491 are located at the midpoint of line WIN-2, and boreholes B317189, 41591, and 0286 are located at the midpoint of line WIN-3. Boreholes located on seismic lines are identified on each corresponding seismic profile by a circle and borehole number. The total depth (TD) of each borehole noted on the seismic profiles is depth below ground surface. The depth of penetration of the borehole is shown on the seismic profiles by a black line that starts at the interpreted ground surface and ends at the approximate TD of the borehole.

Seismic profiles are displayed in reference to a seismic datum, which is an arbitrary reference elevation. Appendix I provides a discussion of the seismic datum. Two scales are noted on the side of each seismic profile. The first is a time scale, in reference to the seismic datum, which shows the time it takes for energy from the source to reflect off acoustic boundaries and return to the geophones. The second scale shows the approximate elevation above mean sea level, which is estimated using a time-to-depth conversion. Because seismic data are recorded in time, the approximate depth to a seismic event is computed using estimated seismic velocities. Seismic velocities were used to convert the tops and bottoms of the channel anomalies and other geologic horizons from time below ground surface (in ms) to depth below ground surface (in ft). Because the velocities are estimated, and actual seismic velocities vary both laterally and vertically, the depths of the channel anomalies denoted are approximate.

Seismic velocities derived from the VSP data acquired in boreholes 44792 and 40591 (located along Indiana Street) demonstrate the velocity variation that can exist in the top 200 ft of section. The average velocities seen in borehole 44792 range from 3,800 feet per second (ft/sec) at 40 ft below ground surface to 5,500 ft/sec at 165 ft below ground surface; and the average velocities seen in borehole 40591 range from 2,250 ft/sec at 40 feet below ground surface to 4,400 ft/sec at 165 ft below ground surface. The velocity variation between the two boreholes is approximately 20 to 40 percent, so depths estimated from seismic lines may vary from actual depths by this percentage. The recorded times of the tops and bottoms of the channel deposits are presented in the text in parentheses next to the approximate depths.

Several anomalous zones are seen on the Indiana Street seismic profiles. These anomalous zones most likely represent the limits of deltaic channel deposition. The seismic anomalies do not represent one large channel sandstone, but rather a series of channel-type depositional sequences, consisting of interbedded claystone, siltstone, and sandstone facies.

Structure is also seen on these profiles in the form of small anticlines and reverse faults. Although structural features can be seen most clearly on the Lower Laramie/Fox Hills reflectors, they are also evident above and below this horizon.

4.1 INDIANA STREET LINE WIN-1

Line WIN-1 displays relatively flat-lying reflectors for the length of the line. The simplified interpretation of line WIN-1 shows three channel anomalies within the Laramie Formation. Borehole 40391, located at station 250, encountered interbedded claystones, siltstones, and silty sandstones in an interval 35 to 62 ft below ground surface. This zone is interpreted to be a channel deposit shown on the profile between stations 186 and 326 at a depth ranging from 35 to 65 ft (40 to 53 ms). The seismic profile at this location displays several high-amplitude events that may be caused by interbedding of sandstone, siltstone, and claystones within the channel. These reflections converge at the edges of the channel anomaly. Borehole 44792, the offset to borehole 40391, encountered silty sandstone from 156 to 168 ft in depth. A channel anomaly was interpreted on the seismic profile between stations 185 and 275 at 156 to 180 ft (77 to 88 ms) in depth.

Figure 4-1 is a composite display showing how seismic events on line WIN-1 are related to the lithology from borehole 44792. First, the lithologic log from borehole 44792 was correlated to the sonic and density logs acquired from 90 to 167 ft in this borehole. Second, a synthetic seismogram was created from the sonic and density logs and correlated to the seismic profile. Third, time on the seismic profile was converted to depth using velocity data obtained from a VSP acquired in this borehole. From this correlation, individual reflections on the seismic profile can be directly correlated to lithology observed in the borehole. For example, the lithologic log shows the change in lithology from a claystone to a siltstone at 141 ft in depth, and a lithologic change from a siltstone to a sandstone at 156 ft in depth. The synthetic seismogram shows positive amplitude reflections from 68 ms (141 ft) and 73 ms (156 ft) that correspond to the lithologic changes on the seismic profile. The sandstones encountered at 156 ft in the borehole are interpreted to be part of a channel sequence.

4.2 INDIANA STREET LINE WIN-2

Seven channel anomalies were interpreted within the Laramie Formation on the line WIN-2 seismic profile. The first channel anomaly extends from station 155 to station 185, and ranges between 77 and 96 ft (40 to 50 ms) below ground surface. The second channel anomaly extends from station 230 to 265, and ranges between 60 and 85 ft (39 to 52 ms) below ground surface. Both of these channel anomalies are characterized by high-amplitude reflectors at the base and top of the channel anomaly that converge at the edges, defining the lateral limits of channel deposition.

The third channel anomaly is located between stations 255 and 463 at a depth ranging from 85 to 174 ft (45 to 72 ms) below ground surface. The reflectors from the top and bottom of the channel anomaly converge at the edges and are generally low in amplitude, indicating a gradational facies change from channel deposits to the surrounding deltaic plain deposits. Lithologic data from borehole B217289, located at station 300, indicates a laminated sandstone sequence displaying cross bedding from a depth of 110 to 133 ft and interbedded sandstones, siltstones, and claystones from 133 to 174 ft. This thick sandstone sequence and interbedded sandstones, siltstones, and claystones corresponds to the anomaly on the seismic profile, thereby supporting the interpretation of a channel deposit.

The fourth channel anomaly extends from station 282 to station 341, at a depth range of 210 to 235 ft (80 to 88 ms). Borehole B217289 encounters a sandstone in this channel from 210 ft to 220 ft (TD). The fifth channel anomaly extends from station 350 to station 416 at a depth ranging from 50 to 75 ft (35 to 45 ms). This thin channel is characterized by high-amplitude, high-frequency reflectors that converge at the edges. The sixth channel anomaly extends from station 430 to station 472 at a depth ranging from 50 to 75 ft (35 to 45 ms). The top of this channel anomaly displays low-frequency reflectors that may indicate a gradational transition with the overlying rocks. The seventh channel anomaly extends from station 450 to station 488 at a depth ranging from 200 to 235 ft (76 to 88 ms). A sharp change in lithology may be indicated by the high-frequency reflectors observed at the top and bottom of this channel deposit anomaly.

4.3 INDIANA STREET LINE WIN-3

Three channel anomalies were interpreted in the Laramie Formation on profile WIN-3. The first channel anomaly is located between stations 265 and 305 at a depth ranging from 120 to 155 ft (68 and 83 ms). This channel anomaly is characterized by converging low-amplitude reflectors on its northern margin that grade into higher amplitude reflectors at its southern margin. The changing character of reflectors across this channel anomaly may indicate a lateral change in lithology within the channel. A second channel anomaly was interpreted between stations 285 and 410 at a depth of 50 to 120 ft (45 to 68 ms). Borehole B317189 is located at station 345. In general, the lithologic log of this borehole describes a 40-ft interval of sandstones, although there are some interbedded siltstones and claystones between the depths of 60 and 100 ft. The depth of these sandstones corresponds with the second channel deposit anomaly.

The third channel anomaly is located between stations 415 and 501, at a depth ranging from between 90 to 150 ft (59 to 75 ms). This channel anomaly displays the same characteristics as the first channel anomaly.

4.4 INDIANA STREET LINE WIN-4

Structure can be seen on the Laramie/Fox Hills reflectors on line WIN-4. At station 265, the Fox Hills Sandstone has been displaced approximately 20 to 40 ft (5 to 10 ms) by a possible high-angle reverse fault. It is not known whether this fault extends to the top of the bedrock.

North of the possible fault, the Lower Laramie/Fox Hills reflectors indicate that a small anticline may be present. The Laramie/Fox Hills reflectors begin to rise at station 510, reach a high point between stations 350 and 310, and then roll into the fault. The strong reflections from the Lower Laramie coals break up on the seismic profile between station 510 and 670. The velocity analysis for this line shows a thick, slow velocity layer near the surface at this location. The following factors could have created this slow velocity layer:

- An unusually thick weathering layer
- A facies change to a slower velocity lithology
- Fracturing in the upper bedrock
- Differences in bedrock lithification or cementation

During acquisition, this slower velocity layer may have absorbed seismic energy. The lack of seismic energy reaching the lower Laramie/Fox Hills reflectors would make imaging these deeper reflectors difficult.

Two possible high-angle reverse faults occur on the Laramie/Fox Hills reflectors between stations 1065 and 1060, and between stations 1100 and 1095. Apparent motion is up to the north on both faults. The displacement on the southern fault is in the order of 20 to 40 ft (5 to 10 ms). Displacement on the northern fault is approximately 20 ft (5 ms). The northern fault appears to be less continuous and either dies out or turns into a bedding plane fault above the lower Laramie Formation. The southern fault appears to extend up the section into the upper Laramie. The projection of this possible fault up to the bedrock-alluvium interface coincides with an interpreted thinning of the alluvium on the upthrown block. Similar to the possible fault on the south end of the section, the lower Laramie/Fox Hills reflectors indicate a small anticline between stations 1225 and 1095. This anticline appears to roll into these faults from the north. The Laramie/Fox Hills reflectors remain relatively flat from station 1225 to the north end of the line.

The deep seismic line (RFD-1) crosses line WIN-4 at station 160 (station 1420 on RFD-1). It is not known whether the faults interpreted on the shallow HR line on Indiana Street are related to the thrust faulting shown on the deep seismic line. It is also not known if the faults interpreted on the Indiana Street seismic line are related to the Boulder-Weld Fault Zone. Kittleson (1992) suggested that the northeast-southwest-trending faults of the Boulder-Weld Fault Zone may extend to the south under RFP. Because of the two-dimensional nature of the Indiana Street seismic lines, the strike of the faults is unknown; however, the apparent motion on the Indiana Street faults is up to the north, which is consistent with the structural style of the Boulder-Weld Fault Zone.

Three channel anomalies have been interpreted on the south end of this line. The first is located between stations 198 and 225 at a depth ranging from 60 to 70 ft (108 to 115 ms). This small channel anomaly is defined by converging low-frequency reflectors. The second channel anomaly is located between stations 305 and 340 at a depth ranging from 60 to 70 ft (100 to 107 ms). High-amplitude reflectors border the top of this channel, possibly indicating a sharp contrast between the channel deposition and the strata above. The channel's lower boundary is not as well defined. The third channel anomaly extends from stations 355 to 440 and ranges in depth from 45 to 60 ft (90 to 100 ms). The lower boundary of this channel anomaly is characterized by high-amplitude reflectors. The discontinuity of the upper boundary reflectors may indicate a gradational lithology change at the top of the channel.

Complex Trace Attribute Displays for line WIN-4

Figure 4-2 shows the interpreted instantaneous phase display for line WIN-4. An instantaneous phase display helps resolve any structural features seen on the seismic profile, which is useful for locating possible faults as they cut through the sedimentary section. The reflectors on each side of the fault are truncated at the fault plane. Three possible faults and the small anticlines that were interpreted on the WIN-4 seismic profile are evident on this display. The faults are approximately located at stations 265, 1060, and 1100. On the north side of each fault, the lower Laramie/Fox Hills reflectors indicate the presence of a small anticline that appears to roll into the fault plane.

Figure 4-3 shows the interpreted instantaneous frequency display for line WIN-4. Although three channel anomalies are located near the south end of the display, there does not appear to be a correlation between high-frequency signal and the interpreted channel anomalies since the high frequency responses seen on the display do not appear to be a result of coherent events.

4.5 INDIANA STREET LINE WIN-5

Strong reflections from the lower Laramie/Fox Hills can be seen on either end of line WIN-5. These reflectors break up in the middle of line WIN-5. The velocity analysis showed a thick, slow velocity layer present near the ground surface in the middle of line WIN-5. This slower velocity layer may have prevented imaging of deeper reflectors due to loss of seismic energy. The lower Laramie/Fox Hills reflectors on the south end of the line display an asymmetric anticline that begins at the south end of the line and continues into the broken data zone near station 430. The anticline climbs gradually from the south end of the line to a high point between stations 300 and 310, then drops more than 50 ft (10 ms) into the broken data zone. From stations 965 to 1075, the Laramie/Fox Hills reflectors show a small, 20-ft (4 ms) syncline; from stations 1075 to 1215 these reflectors appear relatively flat; and from station 1215 to the end of the line these reflectors rise 5 ms.

Three channel anomalies were interpreted on line WIN-5. The first anomaly extends from stations 270 to 413 and ranges from 50 to 120 ft (95 to 118 ms) in depth. The upper boundary of this channel anomaly displays high-frequency, high-amplitude reflectors, signifying an abrupt lithology change between the top of the channel and the overlying strata. The second channel anomaly extends from stations 918 to 957 at depths ranging from 60 to 85 ft (98 to 110 ms). This channel anomaly is defined by high-amplitude reflectors that converge at its edges. The third channel anomaly extends from stations 1023 and 1094 and ranges from 80 to 105 ft (108 to 117 ms) in depth. This thin channel anomaly exhibits strong

440. The displacements seen on the Laramie/Fox Hills reflectors between stations 378 and 395 and on the upper Laramie from stations 390 to 405 and 340 to 350 are probably the result of the static shift and not due to structure.

A channel anomaly was interpreted on line WIN-6 between stations 143 and 204 at a depth of 80 to 105 ft (78 to 95 ms). The channel anomaly is characterized by high-amplitude reflectors that converge at the edges of the channel, indicating sharp contrast between the lithologies in the channel and the surrounding strata.

Complex Trace Attribute Displays for Line WIN-6

The interpreted instantaneous phase display for line WIN-6 (Figure 4-6) shows a broad anticline extending the length of the line. The anticline is most apparent on the lower Laramie/Fox Hills reflectors. These reflectors reveal a break due to a static shift from station 380 to station 395. The static shift also affects the shallow reflectors from station 390 to station 405. A channel anomaly is evident and was outlined on the south end of this display.

The interpreted instantaneous frequency display for line WIN-6 (Figure 4-7) further defines the channel anomaly on the south end of the line. The channel anomaly contains some high frequencies; however, most of the high-frequency responses on the display do not appear to be a result of coherent events.

4.7 INDIANA STREET LINE WIN-7

Velocity analysis for line WIN-7 indicates a thick, slow velocity layer near the ground surface. This slow velocity layer probably absorbed seismic energy during acquisition, making imaging of deeper horizons difficult. The interpreted seismic profile indicates that the Fox Hills Sandstone is located at 400 to 475 ft (200 to 230 ms) below ground surface and is relatively flat. The alluvium varies in thickness from 10 ft (7 ms) on the south end of the line to 25 ft (15 ms) on the north end of the line. No channel anomalies were interpreted on this line.

Complex Trace Attribute Displays for Line WIN-7

Figures 4-8 and 4-9 show the interpreted instantaneous phase and instantaneous frequency displays for line WIN-7. No definite structures or channel anomalies were identified on this line.

5.0 CONCLUSIONS

Several potential channel deposit anomalies were identified on the Indiana Street lines. These channel deposit features are characterized by seismic reflections from the top and bottom of the channel anomaly that converge at the edges of the channel anomaly. Given the two-dimensional nature of the seismic lines, the orientation of these features or their lateral extent cannot be determined. Additional shallow HR seismic data or borehole data are necessary to resolve the three-dimensional nature of these channel deposit features.

Three reverse faults were identified on line WIN-4. Each fault shows approximately 20 to 40 ft of displacement and upward movement in the northern blocks. It is not certain whether the faults extend to the bedrock surface along Indiana Street or to what extent they influence groundwater flow. The relative apparent motion of these faults is consistent with the structural trend of the Boulder-Weld Fault Zone; however, the strike of the faults along Indiana Street is unknown due to the two-dimensional orientation of the seismic lines. It is also not known if these faults are related to thrust faulting seen on the deep seismic line.

Small anticlines, synclines, and faults are evident on the Indiana Street lines. These structural features are most visible on the Laramie/Fox Hills reflectors.

6.0 RECOMMENDATIONS

The acquisition of a seismic line that ties the Indiana Street seismic data with OU2 seismic data is recommended. This line could be used to determine the stratigraphic relationships between the channel anomalies in OU2 and the channel anomalies along Indiana Street and to determine the orientation of the faults seen on the Indiana Street seismic data. This data could be acquired using longer receiver and shot-point intervals, an approach that combines successful data acquisition methodology with cost-saving measures.

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Appendix I

Theory of Seismic Reflection Techniques

SEISMIC REFLECTION TECHNIQUE

A seismic source generates energy that manifests itself as seismic waves. Seismic waves propagate within solids as disturbances traveling through the materials with velocities dependant upon the elastic properties and densities of the materials. Typical commercial seismic sources include explosives and vibrating machinery. These sources generate two types of seismic waves; body and surface waves. Body waves consist of compressional (p) and shear (s) waves. Since most of the energy generated by a seismic source is in the form of p-waves, these waves are of primary interest.

Seismic wave energy attenuates with distance partly due to frictional heat loss through absorption of energy by the host material. Absorption is dependent on the seismic medium; shales have the highest absorption rates, and granites have the lowest. Since seismic waves propagate as spherical wave fronts, the wave spreads out over a spherical area. Thus, the energy per unit area varies inversely as the square of the distance from the source.

A seismic wave will travel through a medium along a ray path until a discontinuity is encountered. A discontinuity can be caused by a change in lithology or fluid content of a porous medium. At a discontinuity, part of the wave will be reflected and another part refracted in accordance with Snell's Law as illustrated in Figure I-1.

The relative amplitude of a reflected wave from the boundary of two layers, Layer 1 and Layer 2, can be expressed in the form

$$R = \frac{d_2V_2 - d_1V_1}{d_2V_2 + d_1V_1}$$

where:

R = reflection coefficient
d = density in grams per cubic centimeter of medium
V = velocity of p-wave through medium

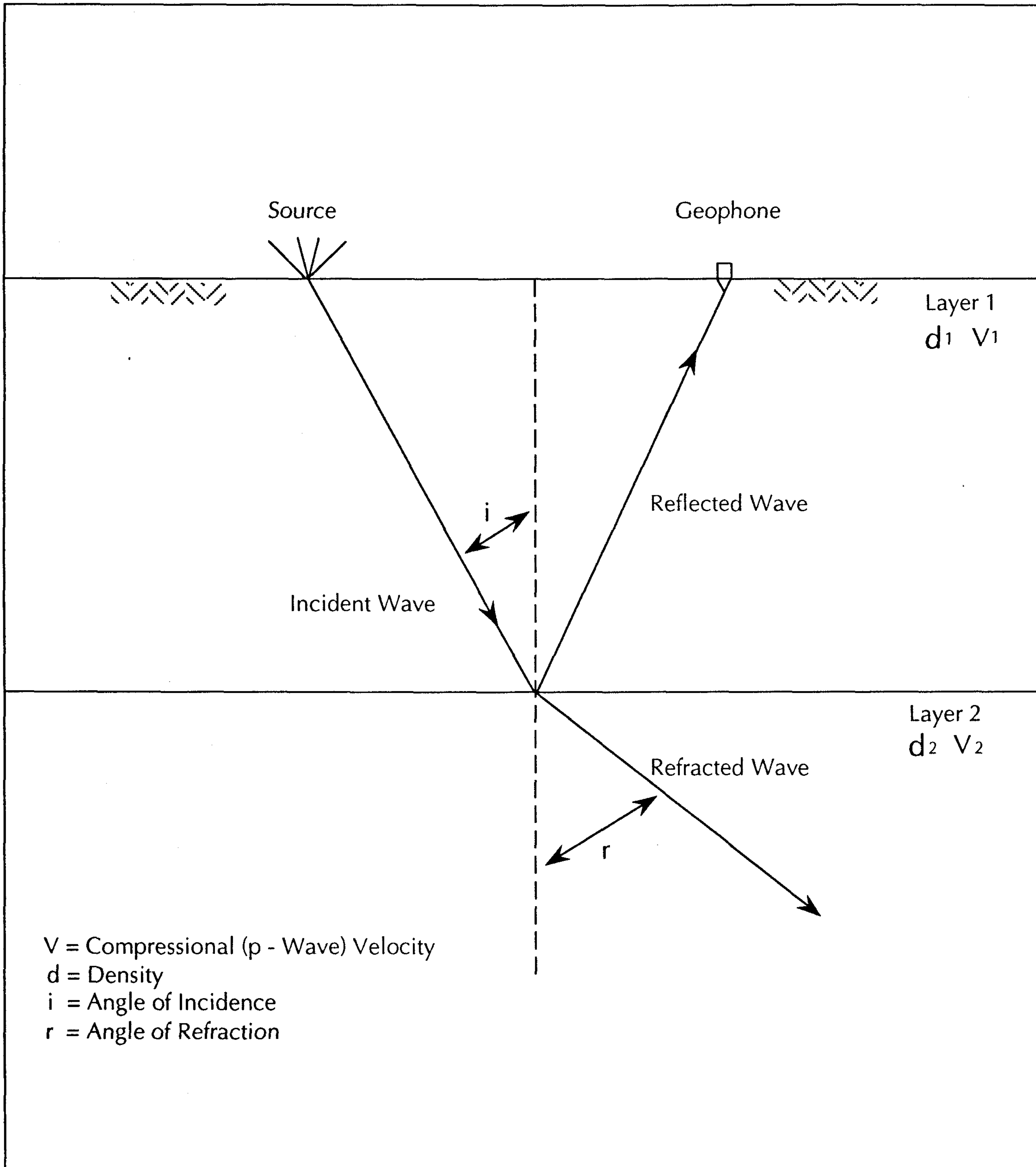

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FIGURE I-1

GEOMETRY OF SNELL'S LAW

The product of the density and velocity is known as the acoustic impedance. If the acoustic impedance increases across an interface, then the reflected wave has a positive amplitude. Conversely, if the acoustic impedance decreases across an interface, the reflected wave has a negative amplitude.

The refracted p-wave makes an angle, r, expressed by the relation

$$\frac{\sin i}{\sin r} = \frac{V_1}{V_2}$$

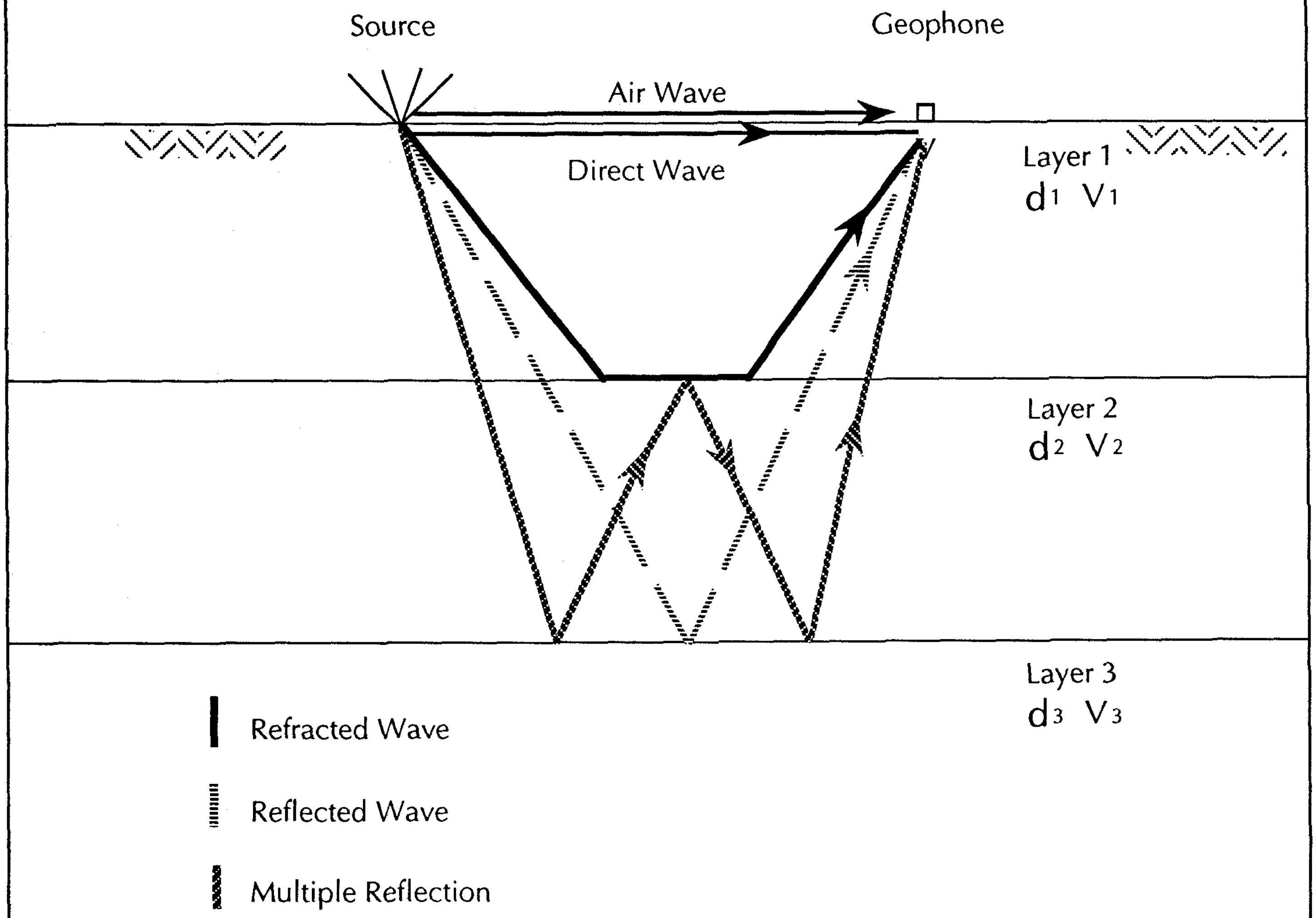
where:

i = angle of incidence
r = angle of refraction
V_1 = velocity of p-wave through Layer 1
V_2 = velocity of p-wave through Layer 2

When sin i = V_1/V_2, sin r becomes unity and r becomes 90°. The refracted wave does not penetrate the medium, but travels along the interface between the two materials. Angles i and r are measured relative to the normal at the intersection of the interface and the incident wave.

Where seismic waves strike any irregularity along a surface such as a corner or a point where there is a sudden change of curvature, the irregular feature acts as a point source radiating waves in all directions. Such radiation is known as diffraction. The amplitude of a diffracted wave falls off rapidly with distance away from a source.

Another seismic phenomenon, the interbed multiple reflection is illustrated in Figure I-2. A wave reflects upward from the interface between Layer 2 and Layer 3. Returning to the surface, the wave reflects downward from the Layer 1 - Layer 2 interface, because any change in acoustic impedance at an interface boundary can cause a reflection. The wave again reflects from the top of Layer 3 and successfully returns to the surface.



V = Compressional (p) Wave Velocity

d = Density

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FIGURE I-2

TYPES OF SEISMIC WAVES

Figure I-2 also shows the types of seismic waves generated by a surface source that will be detected by a geophone. The air wave travels at the speed of sound in air (approximately 1,100 feet/second (fps). The direct wave travels from the source to the geophone within the uppermost medium. This wave is normally faster than the air wave but slower than the other illustrated waves. The refracted wave has the earliest arrival time. The reflected wave is slower than the refracted wave. A multiple reflected wave has a longer arrival time than the reflected wave because of the greater distance traveled. Because of the varying velocities of the different waves it is possible to design seismic field parameters to record the waves of primary interest.

According to signal theory, the amount of information present in a seismic reflection signal is proportional to the bandwidth. The bandwidth of a seismic signal is the range of frequencies contained within. The maximum frequency that can be recorded reliably is equal to one-half of the sampling frequency or rate. This is known as the Nyquist frequency. At a 0.25-millisecond (ms) sampling rate, the Nyquist frequency is 2,000 hertz (Hz).

COMMON DEPTH POINT METHOD

Seismic reflection techniques build on basic seismic principles. Development of digital recording techniques in the 1960s catalyzed great advances in seismic reflection acquisition, processing, and interpretation. Seismic noise is any unwanted signal sometimes it is random and other times it is coherent (e.g., an operating water pump or a nearby electric powerline). To reliably interpret a seismic event, the signal-to-noise (S/N) ratio must be at least 1:1.

The Common Depth Point (CDP) technique has enabled the recording and display of reflection events that have S/N ratios less than unity. The CDP technique records reflections from multiple offsets at different source and receiver pairs as illustrated in Figure I-3. For each CDP the number of source and receiver pairs recorded is called the fold. Six fold data, also called

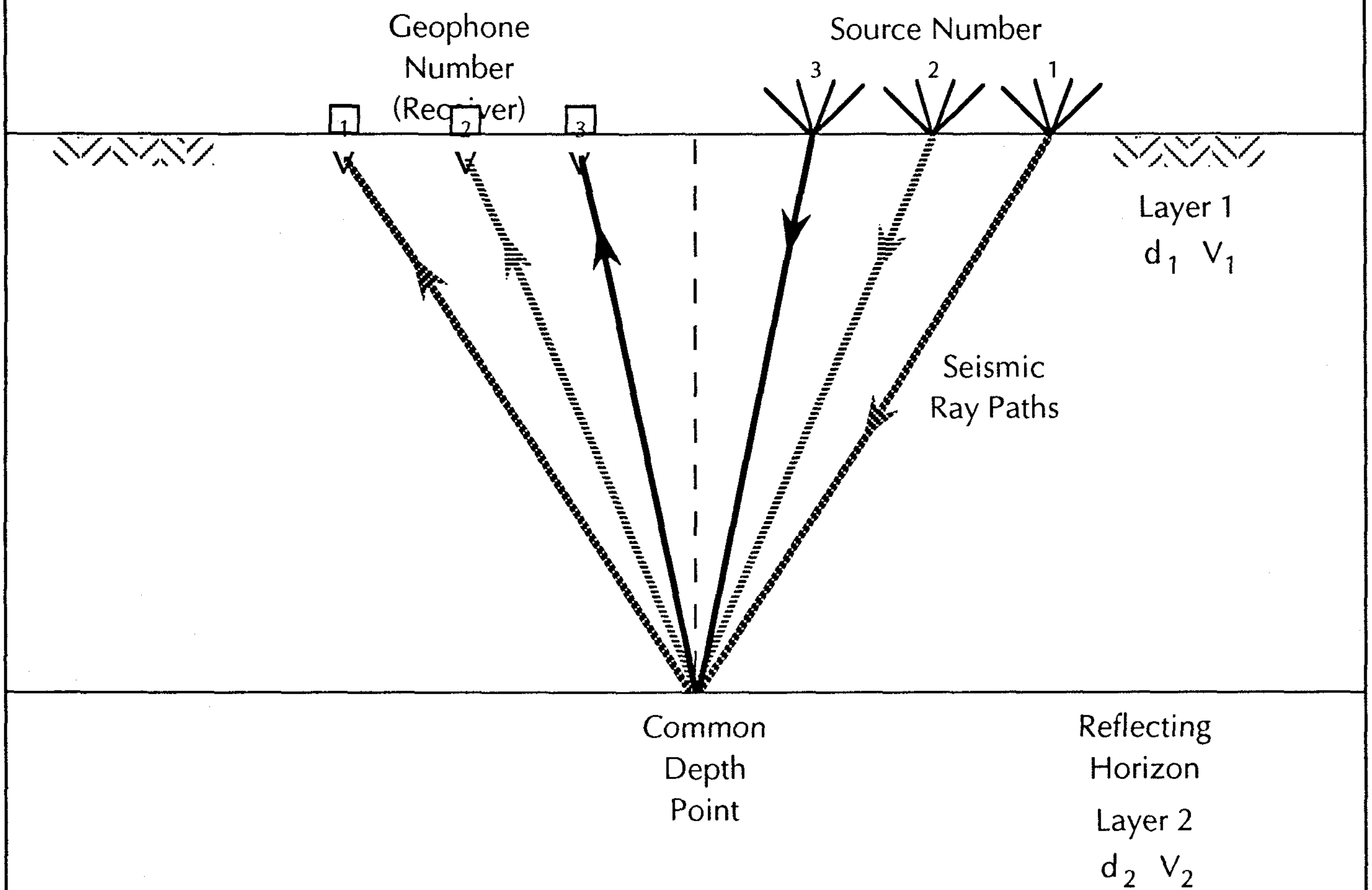

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FIGURE I-3

COMMON DEPTH POINT TECHNIQUE

600 percent stack, has six source and receiver pairs. The S/N ratio doubles for each quadruple increase in the CDP fold. The CDP fold can be calculated by:

$$CDP\ fold = \frac{receiver\ spacing}{2\ x\ source\ spacing}\ x\ number\ of\ recording\ channels$$

The processing of seismic reflection data is a statistically intensive procedure and requires human guidance at each step. After acquisition, the seismic reflection data are processed from source record format into CDP record format. Each CDP record will have the same number of traces equal to its fold. Because the distance between source and receiver is greater for the longer offsets of a reflection event (source-receiver 1 as opposed to source-receiver 3, Figure I-3), the recorded reflection event itself will record at a later time. The difference in time for a particular event on adjacent traces is termed normal moveout. Data are corrected for normal moveout during processing, and all traces in the CDP record are merged or summed together (stacked). This enhances the real events and cancels undesirable random noise, thus increasing the S/N ratio.

Before stacking, data are corrected for elevation variations, resulting in a static correction. After stacking, automatic statics are performed to correct for velocity variations in the near-surface weathered layer. Digital filters are applied at various steps in the processing to eliminate undesirable noise and enhance the reflection events. Post-stack filtering may include enhancing individual reflection events to improve the interpretation by statistically comparing adjacent seismic traces for continuous events versus random noise.

Seismic events recorded from a geophone appear to arrive from directly beneath the geophone. Where the reflecting horizon is dipping, the position of the event is incorrect. Dipping events migrate downdip. If necessary, these events can be migrated back to their true location. Depending on the data and objectives of the interpreter, this process can be done either before or after stacking (pre-stack or post-stack migration).

Recording shallow reflection events requires modification of standard seismic reflection techniques. In standard seismic reflection techniques 12 or more geophones are grouped together as an array. Typical distances between groups are tens to hundreds of feet. In shallow high-resolution (HR) seismic reflection work geophone arrays are eliminated and individual geophones are used. Geophone spacings are reduced to a few feet, depending on the depth to the shallowest target. Shallower targets require closer geophone spacings. The number of recording channels needed is dependent on the depth to the deepest target of interest and the geophone and source spacing. Vertical resolution is limited by the bandwidth of the recorded signal and the sampling frequency. Horizontal resolution is limited by the bandwidth of the recorded signal and the geophone spacings.

SEISMIC DATUM

The seismic datum is an arbitrary reference surface that corrects seismic data for local topographic variations. The start time of each record is corrected to the seismic datum. In general, if this reference datum is below the ground surface then some shallow data will be lost. If the datum is above the ground surface then the earliest seismic events are recorded and preserved on the seismic profile. Conventional seismic reflection utilizes a seismic datum below the ground surface because there is little interest in shallow events; however, the high-resolution seismic programs at Rocky Flats Plant are targeting the early or shallow events. Therefore, a seismic datum above the ground surface is used. For example, if a borehole has an elevation of 5,900 feet (ft), the seismic line intersecting the borehole might have a seismic datum elevation of 5,975 ft. If a sandstone was encountered in the borehole at a depth of 120 ft, the seismic depth of the sandstone would be 195 ft on the seismic profile because the seismic datum is 75 ft higher than the borehole ground surface elevation.

Appendix II

Seismic Reflection Equipment

INSTRUMENT SPECIFICATIONS

- EG&G Geometrics ES-2420 Digital Reflection Seismograph
- Mark Products L-40 A-2 Geophones
- Input/Output RLS-240M Rota-Long Switch
- Input/Output Synchrafone I and II Source Synchronizer
- Mountain Systems Service Geophone String Tester

In the event of unforeseen circumstances, equivalent instruments will be substituted for equipment listed below.

EG&G GEOMETRICS ES-2420 DIGITAL REFLECTION SEISMOGRAPH

The following specifications apply to an operating environment of 0 to 40 C°, after a 5-minute warmup period (EG&G Geometrics 1984).

Analog Performance Specifications

Preamplifier Gain:	32 (30.1 decibels [dB])
	64 (36.1 dB)
	128 (42.1 dB)

Selected by switches on printed circuit board.

Input Impedance:	Differential, 20K ohms, .01 microfarads (μfd)
	Common Mode, 5K ohms, .02 μfd

Maximum Differential	@ 30 dB, 0.640 volts (V) peak to peak
Input Voltage:	@ 36 dB, 0.320
	@ 42 dB, 0.160

Maximum DC Common Mode

Voltage: 10.0 V

Transient Protection: Transients with energy less than 0.75 Joule and voltage less than 200 V will not damage instrument

Alias Filters:

6 dB Frequency (F_c)(Hertz [Hz])	Stop Band Frequency (Hz)	Stop Band Attenuation (dB)
45	125	80
180	500	80
360	1,000	78
720	2,000	78
1,440	4,000	78

6 dB corner frequency tolerance:	3% max
Time delay, constant from 5 Hz to Fc within	± 2%
Time delay similarity between channels	± 2%

Low Cut Filter: Frequency: 5 to 320 Hz in 5 Hz increments

3 dB corner frequency tolerance: 3% max

Type: Butterworth

Attenuation slope: 18 dB/octave

Notch Filter: 50 or 60 Hz or out, selected from front panel

6 dB bandwidth 9 Hz typical $F_o \pm 3.65$ min ± 6.80 max

50 dB bandwidth 0.5 Hz typical $F_o \pm 0.1$ min

Floating Point Digitizer

Instantaneous-floating-point amplifier with 16 gain ranges (6 dB per step) followed by a 15-bit analog-to-digital converter. Amplifier gain range is automatically selected for each sample to maximize the precision of the mantissa value.

Exponent:	4-bit unsigned binary number representing the gain range, where zero represents maximum gain (minimum signal)
Mantissa:	15-bit, twos-complement binary
Full scale input voltage:	± 10.24 V
Gain step relative accuracy:	0.1%
Analog/Digital (A/D) converter accuracy:	0.2%
A/D converter linearity:	0.01%

System Response

Signal to Noise Ratio:	100 dB (3 to 180 Hz, 42 dB preamp gain, 600 ohm input, notch & low-cut filters out, alias filter set to 180 Hz)
Frequency Response:	Lower 3 dB frequency, 1.6 Hz ±10% Upper 3 dB frequency, determined by alias filter
Gain accuracy:	1%
Gain similarity between channels:	2%
Total Harmonic Distortion:	0.05% FPA in minimum gain Preamp gain minimum Input: 0.226 voltage root mean square (Vrms) 3 to 1,000 Hz
Crossfeed:	<80 dB, 3 to 2,000 Hz
Timing:	Time base accuracy 0.002%

Sample skew:	Within 8 channel group, 1/40 ms/channel.

<u>Operating Characteristics</u>

Sample Interval, write-to-memory:	1/4, 1/2, 1, 2, or 4 ms Front panel selectable
Real time clock:	Built in digital clock with time of day and day of year. Battery backup provides continuous timekeeping. Basic accuracy 3 seconds per month at 25° C. Time recorded on tape.
Maximum Record Length:	Set from front panel to maximum of 99 seconds in direct-to-tape. In stack-to-memory maximum length determined by sample interval: 1/4 ms 4.096 seconds 1/2 8.192 1 16.384 2 32.768 4 65.536
Delay Start:	Postpones sampling of data by front-panel selected delay up to 9.999 seconds in 0.001 second increments.
ES2420 Acquisition Control Unit (ACU) Power Supply:	Operates from 10 to 18 V DC
DP2420 Printer Power Supply:	Operates from 10 to 14 V DC
DMT2420 Tape Drive Power Supply:	Operates from 10 to 16 V DC

<u>Dimensions</u>

ACU:	28 x 16 x 23.5 inches (22.5 with 71 x 41 x 60 cm cover removed)
Expansion Module:	same as ACU
Portable Tape Deck:	same as ACU

Plotter:	15 x 15 x 18 inches 38 x 38 x 46 cm

Weights

Acquisition Control Unit:	110 lbs (50 Kg) with 4 channels 7 lbs (3 Kg) for each additional 8-channel board set
Printer:	40 lbs (18 Kg)
Portable Tape Deck:	100 lbs (45 Kg)
Environmental:	Operating temperature, 0 to 45 C° continuous operation with built-in forced air cooling. Can be operated in cyclic conditions to temperature of 50 C°. Storage temperature - 40 to 70 C° Humidity 10 to 95% noncondensing May be operated in vertical position in light rain (cover closed on tape recorder, protection for plotter) Weatherproof with transit lid closed

CRT Display

512 by 512 dot matrix graphic display of seismic data and acquisition parameters. Can display at maximum expansion of one dot per sample, or compressed in 3 dB steps up to maximum of 16,196 samples on screen. Also displays a time cursor and scale lines and selected parameters (battery voltage constant, file number, and status messages).

TAPE DATA FORMAT

Tape format:	Nine-track, SEG D, 2 1/2 byte, multiplexed
Data density:	1,600 bits per inch (bpi)

Block size:	Fixed blocking, equal to an integral number of scans, as close as possible to a user selected maximum or ungapped
Channel set descriptor:	One for all channels
Sample skew:	Not written to tape. For each set of Channels (usually 8) supported by a Data Acquisition Memory (DAM) board - Preamplifier Filter (PF) board pair, sample skew starts at zero and increased by 1/40 ms per channel. The maximum sample skew for any channel in the system is thus 7/40 ms.
Data word:	Ones complement, twenty bits with a one-bit sign, four-bit binary exponent, and 14-bit mantissa. The least significant bit (LSB) is zero.

GEOPHONE SPECIFICATIONS - MARK PRODUCTS L-40 A-2

The following specifications are found in the operatiosn manual (Mountain Systems Service, Undated).

Standard Frequency Range	100 Hz
Frequency Tolerance	$\pm$ 7%
Standard Coil Resistance $\pm$ 10% (Ohms)	325, 510, 780
Distortion @ Resonance, @ 0.7 in/sec	0.2% MAX
Transduction Constant, V/in/sec	0.031 coil resistance (Rc)
Open Circuit Damping	$\frac{47.9}{f}$
Coil Current Damping	$\frac{20.8\ Rc}{f\ (Rc + Rs)}$
Suspended Mass, Grams	5.7
Case-to-Coil Motion, p-p in	0.080
Intrinsic Power Sensitivity milliwatts (mw)/in/sec	0.96
Basic Unit Diameter, in	1.25
Basic Unit Height in	1.37
Basic Unit Weight, oz	5.0

ROTA-LONG SWITCH SPECIFICATIONS - INPUT/OUTPUT RLS-240 M

The following specifications are presented in summary form from the operations manual (Input/Output, Inc., 1981a).

- 240 input stations
- 120 recording channels
- Unlimited types of recording configurations
- Auxiliary connector permits diagnostic cable tests with an ohmmeter or I/O Break Chek
- Size: 20 in wide x 20 in tall x 6.50 in deep
- Weight: 40 lbs

SYNCHRAFONE - INPUT/OUTPUT SYNCHRAFONE I AND II SOURCE SYNCHRONIZER

The following specifications are presented in summary form from the operations manual (Input/Output, Inc., 1981b).

- Contains radio within unit
- Four privacy codes
- Digital display of uphole time
- Time break and uphole time output from Encoder
- Firing time repeatability at 1 ms
- Available as truck mount or portable
- Wire line and radio modes

REFERENCES

EG & G Geometrics. 1984. ES-2420 Digital Reflection Seismograph Operation Manual.

Input/Output, Incorporated. 1981a. RLS-240M Manual Rota-Long Switch Operations Manual, 12 pp.

Input/Output, Incorporated. 1981b. Synchrafone Series Operations Manual, 111 pp.

Mountain Systems Service. Undated. Geophone String Tester (GST) Operators Manual, 10 pp.

Appendix III

Data Processing

PROCESSING INFORMATION PRESENTED ON A SEISMIC REFLECTION PROFILE

Labeling on a seismic reflection profile (section) indicates the type of seismic reflection data and provides information about the field acquisition parameters and the data processing steps. As shown for WIN-4 the label is located on the right side of the seismic section. Above the actual reflection data, the surface topography is presented.

SIDE LABEL

At the top of the side label on the far right of the section indicates the name of the client ordering the data processing services (i.e., Ebasco Services Incorporated for EG&G). Below the client name is the seismic line identifier (i.e., WIN-4). The prospect "West Indiana Street" designates the area of data collection. The county and state location are given beneath the prospect name. At the top of the side label is a directional arrow pointing towards the beginning of the line with the cardinal direction denoted (in this case, north).

RECORDING PARAMETERS

Line 1 of the side label indicates the recorder of the seismic data (i.e., Ebasco Services), and the recording date (June 1992).

Line 2 indicates the instrument manufacturer and model (i.e., EG&G 2420), and the sample rate 0.25 ms (the time interval at which each seismic channel is polled for a data value).

Line 3 indicates the type of gain or amplifier setting for each channel. The EG&G 2420 seismograph has a 16-bit analog to digital converter with instantaneous floating point (IFP) gain. The amplifier setting for each channel is adjusted dynamically by the seismograph based on the input signal amplitude. Line 3 also indicates the type of seismic source used (i.e., 8-gauge electric capsule).

Line 4 indicates the explosive array (source pattern). Seismic reflection surveys may utilize more than one source of the same type simultaneously. The source pattern can be in-line or in a geometric pattern, such as a rectangle. In this case the source was located 5 feet (ft) perpendicularly off the line. Line 4 also indicates the charge size (i.e., 300 grain).

Line 5 shows the recording tape format, the SEG-D 1600 BPI. The SEG-D format is the standard magnetic tape format 'D' as specified by the Society of Exploration Geophysicists (SEG, 1980). 1600 BPI means a recording density of 1,600 bits per inch. Line 5 also gives the shot hole depth (or shot burial depth).

Line 6 on the left shows the number of traces or recording channels used and the source interval. The source interval is the ground distance between successive seismic shots.

Line 7 shows the record length. This is the total time (500 milliseconds [ms]) that the seismograph recorded. Line 7 also shows the geophone interval, the distance between each geophone on the ground.

Line 8 shows the elapsed time. This is the amount of time that elapsed while the seismograph was recording, but before the seismic source was activated (0 ms). Sometimes a delay in the shot detonation is added to ensure that the source timing mechanism (synchronizer) is properly synchronized with the seismograph. Line 8 also shows the station interval to be 2 ft. This is the ground distance between receiver (geophone) stations.

Lines 9 through 14 (left side) shows the recording filter settings. The low-cut filter is given as the frequency start of the attenuation of lower frequencies. The low-cut filter slope is the rate of attenuation. The high-cut filter is the frequency start of attenuation of higher frequencies. The filter slope for the high-cut filter is also shown. The last filter item is the notch filter. When recording in areas near electric power lines, excessive 60 hertz (Hz) noise can be rejected using the notch filter.

Line 9 (right side) shows the geophone array to be "single in-line." This means that a single geophone was used at each receiver station.

Line 10 (right side) shows the geophone's natural resonant frequency (i.e., 100 Hz). This is the vibration frequency of the geophone in the absence of an oscillatory disturbing force.

Line 11 (right side) displays the seismic line orientation.

Line 12 (right side) shows that trace one (i.e., the first seismic trace) starts on the south end of the seismic line.

Line 14 (right side) indicates the Common Depth Point (CDP) fold, in this case 24 fold.

Below the recording parameter box is the seismic data processing center's logo (i.e., Geotrace Technologies, Inc).

At the bottom of the recording parameters box is a diagram of the geophone cable geometry. It shows the shotpoint location in reference to the zero offset trace location, the first trace location in reference to the shotpoint, and the last trace location in reference to the shotpoint.

PROCESSING SEQUENCE

The next large box displays the final processing sequence.

DATA PROCESSING

The following is a brief description of the processing algorithms applied to the seismic data. Some algorithms may be applied more than once with different parameters. Subsequent applications are use to enhance different aspects of the data.

DEMULTIPLEXING

In the field, seismic data were recorded by the EG&G ES-2420 seismic acquisition unit in multiplexed format. Multiplexing is a process whereby multiple channels of data can be transmitted through a single channel without loss of information. Multiplexed data samples are stored on tape in channel sequential order, whereas demultiplexed data samples are stored in time sequential order. The seismic data traces are demultiplexed in the initial data processing stage.

GAIN RECOVERY

The EG&G ES-2420 seismograph contains an automatic digital gain amplifier, which separately records the value of gain applied to each incoming sample. A seismic wave undergoes severe amplitude attenuation as it travels through the earth and the digital gain amplifier compensates for this by attempting to restore seismic wave amplitudes to initial levels. In the data processing stage the different gains applied by the field instrument are equilibrated to reproduce data traces that are consistent with respect to their true amplitudes. Associated with gain recovery is spectral balancing. This process increases the amplitudes of the data with respect to frequency. Frequencies from 60 to 600 hz were boosted on the WIN Seismic lines.

STATIC CORRECTIONS

The quality of the final seismic section is dependent upon the proper utilization of static corrections. Static corrections are applied to seismic data to eliminate the effects of elevation, the weathering zone thickness and velocity variation. The greater the variation in the surface elevation or near surface velocities, the more important static corrections become. A refraction statics program was performed on the data to handle the near surface statics effects from the lateral and vertical velocity variations.

DECONVOLUTION

Convolution is a mathematical process of passing one function through another to form a third function. The appearance of a final seismic section is a result of the convolution of a seismic source signal with the earth's reflectivity characteristics. An infinite bandwidth seismic signal convolved with the earth's reflectivity series would produce a very detailed cross-section of the earth's subsurface.

A seismic source signal in the shape of a spike in the time domain has an infinite frequency bandwidth. Unfortunately, seismic sources do not resemble perfect spikes. Since the final seismic section is the result of filtering the reflectivity of the earth with the seismic source signal, an inverse filter can be designed (a deconvolution process) to recover the true reflectivity.

A convolution with a "spike" (or broad-band frequency wavelet) will reproduce the original function. The goal of deconvolution is to observe the spectrum of the seismic source pulse and design an inverse operator which reduces the pulse to a "spike." In completing this task, the processing geophysicist can apply the inverse operator to the reflected signals, thereby removing the effect of the source signal in them.

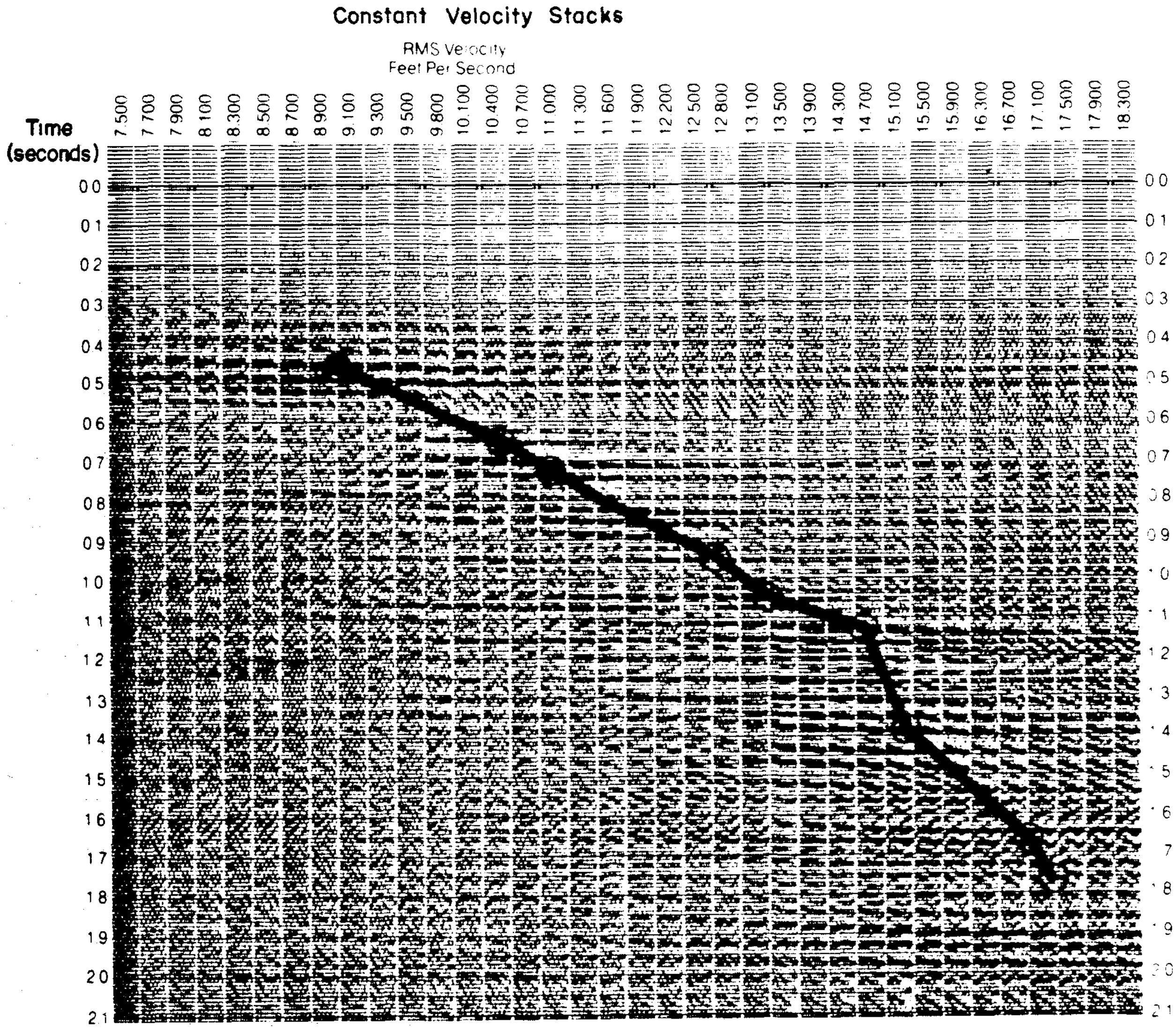
CDP GATHERS/VELOCITY ANALYSIS

All data processing performed up to this stage has been based on sequential data for every shotpoint. The data are now rearranged by CDP, gathering into CDP format, whereby all the traces common to one depth point are collected together.

The difference in arrival times at two geophone locations for the same reflection is termed normal moveout. This time difference can be utilized to estimate seismic velocities of different reflecting horizons. After these interval velocities are assigned to the CDP gathered data, the resulting seismic section is examined for anomalous character that may indicate further velocity analysis is needed.

Commonly constant velocity stacks are made to analyze the seismic velocities. An example is shown in Figure III-1.

STACKING



Interpeted Velocity Analysis Function for Stacking CDP Data

Source: Dobrin, 1976

E G & G Rocky Flats, Inc. February 1993

FIGURE III-1

COMMON DEPTH POINT
VELOCITY ANALYSIS

Stacking the seismic reflection data is one of the most important steps in the data processing sequence. Seismic reflection data are recorded multifold to improve the signal-to-noise (S/N) ratio. For random noise (i.e., airplanes, raindrops, cars, etc.) the improvement in the S/N ratio is equal to the square root of n, where n is the CDP fold. Random noise effects on the data are reduced and multiple reflections (multiples) are attenuated by the stacking process. Properly stacked seismic data will result in a significant reduction of noise within the final seismic section.

DISPLAY PARAMETERS

The display parameters box describes the manner of displaying the seismic section. The number of seismic traces displayed per inch is 10. The vertical scale is 50 inches per second (i.e., one second of data requires 50 inches to display). The seismic polarity is normal. Reverse polarity is the other option and means that the final amplitude of the seismic traces has been multiplied by -1. For stratigraphic interpretation of seismic reflection data it is sometimes useful to interpret on reverse polarity seismic sections. The display gain is 0.8. This means that all of the amplitudes were scaled (i.e., multiplied) by a factor of 0.8. This value is determined from visually inspecting the data. The display date is September 1992 (i.e., the date when the seismic section was displayed).

CDP FOLD DISPLAY

At the top of the seismic section is a graphical display of the CDP fold (see Appendix I). Near station 130, the fold exceeds 30; whereas, on the ends of the line, the fold is less than 10.

SURFACE PROFILE

Below the CDP fold display box is the surface elevation profile. The elevation is displayed on both ends of the profile. The solid line indicates the surface elevation.

VELOCITY ANALYSES

Below the surface and weathering proflie are several boxes displaying the results of the stacking velocity analyses. Each analysis is displayed with the station location below. In the analysis box on the left are the two-way times and on the right the corresponding root mean squared (RMS) seismic velocity used to stack seismic reflection events.

SEISMIC DATA DISPLAY

Immediately above the seismic reflection data display are station numbers. On the left and right side of the data display is the two-way time scale (in seconds). Below each station is displayed one stacked seismic data trace, starting at time 0.0 second and ending at time 0.50 second. Positive reflection events are displayed as dark-shaded positive peaks, with deflections to the right. Negative reflection events are displayed unshaded with deflections to the left.

FINAL SECTION

The final seismic profile was displayed using a combination of variable area and wiggle trace. The wiggle trace display enhances the wavelet shape, giving added insight to stratigraphic interpretation. The variable area display emphasizes the wavelet amplitude, enhancing the lithologic identification.

MIGRATION

Steeply dipping structures in the subsurface will be displaced from their true position on the seismic profile due to raypath imaging inconsistencies. Migration processing can effectively remove the raypath inconsistencies and return a reflector to its true position on the final seismic section. Migration processing becomes an increasingly important tool when there are steeply dipping structures present. The effect of the migration processing was noticeable when comparing the migrated and unmigrated seismic sections. Migration improves the S/N ratio by approximately 6 decibels (dB).

COMPLEX ATTRIBUTE ANALYSIS

A seismic wave involves moving particles of matter out of their equilibrium positions and thus involves kinetic energy. Hence, the conventional seismic trace may be thought of as a measure of kinetic energy. The particle motion is resisted by an elastic restoring force so that energy becomes stored as potential energy. As a particle moves in response to the passage of a seismic wave, the energy transfers back and forth between kinetic and potential forms. The quadrature trace may be thought of as a measure of potential energy (Taner et al., 1979).

The quadrature (or complex) trace can be calculated from the conventional seismic trace. From the quadrature trace several attributes can be calculated. These are as follows:

1) Reflection strength
2) Instantaneous phase
3) Instantaneous frequency

The reflection strength is a measure of the total amplitude of the seismic trace independent of peaks and troughs. The reflection strength is also a measure of the reflection character. It is sometimes an aid, for example, in distinguishing between reflections from massive reflectors and those which are interference composites. Unconformities often show changes in reflection strength character as the subcropping beds change. Seismic sequence boundaries tend to have fairly large reflection strengths.

The instantaneous phase is a quantity which is independent of reflection strength. Instantaneous phase emphasizes the continuity of events. Weak coherent events are thus brought out. Phase displays are especially effective in showing pinchouts, angularities, and the interference of events with different dip attitudes.

The time derivative of the instantaneous phase is called instantaneous frequency. The instantaneous frequency can vary quite rapidly. Sometimes it is useful to smooth frequency measurements with a weighted function. Petroleum exploration applications have found instantaneous frequency to be a good indicator of condensate reservoirs. This is the first use of instantaneous frequency to shallow applications. Seismic reflection events from interbedded fluvial deposits have a high instantaneous frequency response (Irons and Lewis, 1990). The instantaneous frequency plots were used as an auxiliary interpretation tool; however, the interpretation relied mostly on the final stacked profiles.

REFERENCE

Irons L.A. and B. Lewis. 1990. Shallow High-Resolution Seismic Reflection Investigation on a Hazardous Waste Site. Proceedings of the Fourth National Outdoor Action Conference on Aquifer Restoration, Ground Water Monitoring, and Geophysical Methods. Number 2. Presented by the Association of Ground Water Scientists and Engineers, Division of NWWA. pp 1129-1142.

SEG (Society of Exploration Geophysics) Technical Standards Committee. 1980. Digital Tape Standards.

Taner, M.T., F. Koehler, and R.E. Sheriff. 1979. Complex Trace Analysis: Geophysics, 44, 1041-1063.

Appendix IV

Vertical Seismic Profiles

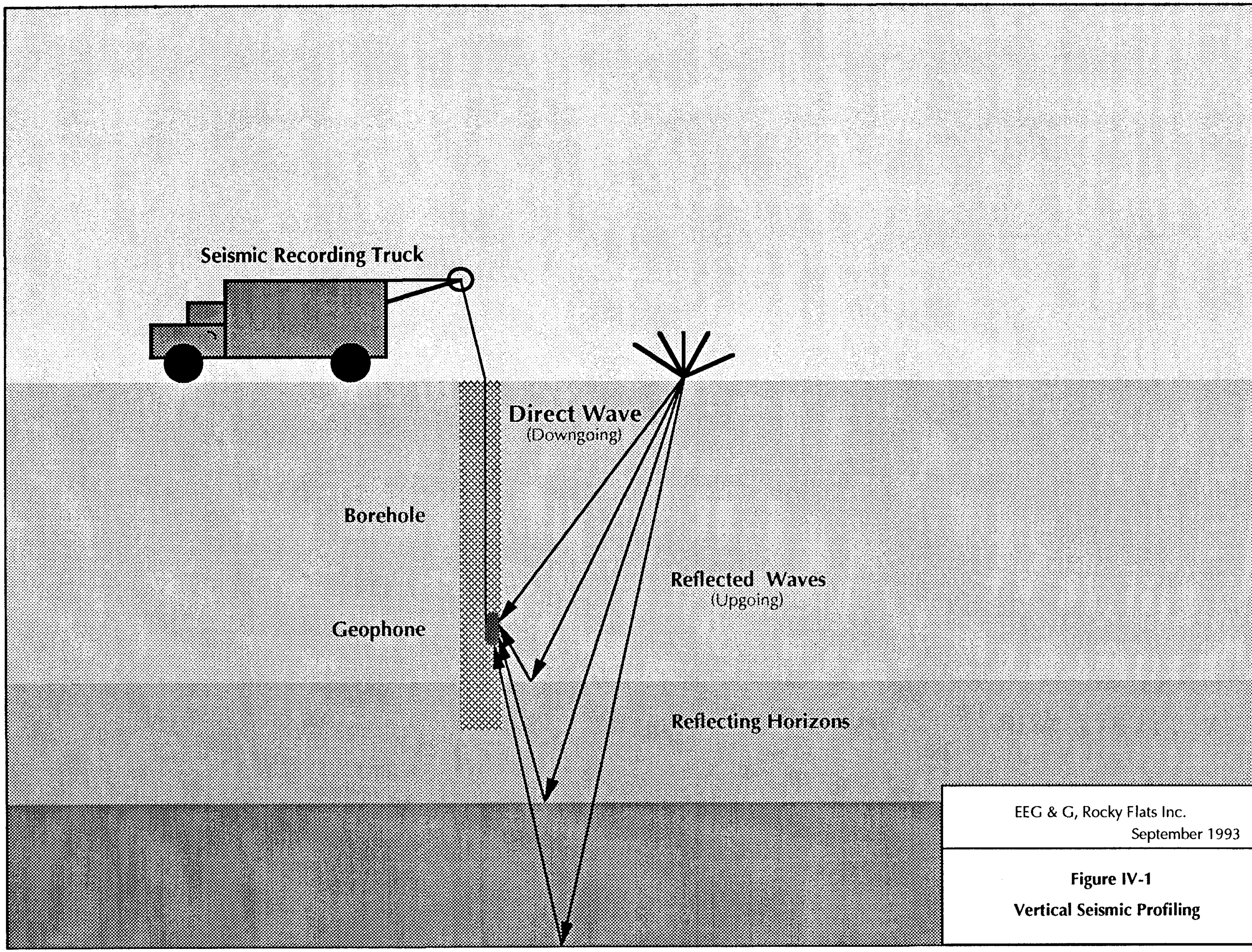
1.0 INTRODUCTION

Vertical seismic profile (VSP) data were acquired at four wells at the Rocky Flats Plant during the Phase II Geologic Characterization Data Acquisition. The primary objectives of the VSP acquisition, processing, and analysis were to identify specific reflectors on the high-resolution seismic data and correlate them to lithology, and to determine bedrock velocities. Two of the VSP's were performed along Indiana Street for correlation to the WIN seismic lines, one VSP was performed in the west spray field for correlation to seismic line WSF-1, and one VSP was performed near the current landfill to gain shallow information near the deep seismic line RFD-1.

2.0 VERTICAL SEISMIC PROFILING METHODOLOGY

VSP is a borehole geophysical method that utilizes an energy source and recording devices (i.e., geophones) to identify subsurface reflectors that exhibit contrasts in acoustic properties. VSP data may be used to convert the two-way time measurements observed on the high-resolution (HR) seismic profiles to depth. Since the borehole lithologies are known from lithologic and borehole geophysical logs, reflectors present on the VSP data may be identified with respect to lithology, time, and depth. VSP data can also be compared and correlated with synthetic seismograms generated from sonic and density logs.

In general, a VSP is acquired by placing a seismic source at the ground surface and geophones in the borehole at specified depths. The seismic source is activated and the seismic energy is recorded by the downhole geophones. Many types of seismic energy are recorded, the two most important being the downgoing (direct) and upgoing (reflected) waves (Figure IV-1). The downgoing VSP energy is analyzed for the first arrival time of the compressional wave. This analysis provides information on the velocity of the subsurface medium. These velocity data are useful when correlating the VSP data to a borehole synthetic seismogram and to HR seismic reflection data. The upgoing energy is the seismic energy reflected from horizons near the borehole that exhibit contrasts in acoustic properties. The upgoing energy provides information on the depth of subsurface reflectors.



EEG & G, Rocky Flats Inc.
September 1993

Figure IV-1
Vertical Seismic Profiling

3.0 VSP DATA ACQUISITION

VSP data were acquired in Wells 44792, 42392, 42292, and 40591. A comprehensive suite of borehole geophysical logs were also acquired in these wells and included:

- Sonic
- Density
- Resistivity and conductivity
- Neutron
- Natural gamma
- Temperature
- Fluid resistivity
- Caliper
- Spontaneous potential

All borehole geophysical logs were digitally acquired at 0.1 foot (ft) intervals in each well. VSP data were collected at 2 or 4 ft intervals in each well.

The VSP source selected for this program was a Bolt Air Gun. An air gun source is an effective seismic source in terms of its energy and frequency content. However, due to the mechanical opening and closing of the air gun port, the source signature may be characterized by inconsistent timing delays between successive firings. This attribute was overcome by placing a signature geophone in close proximity to the air gun to compensate for these delays.

The borehole recording device used to record the seismic energy consisted of two 100 hertz (hz) geophones connected in series. The seismic data were transferred via an electrical cable to a EG&G ES-2420 seismograph, that digitally sampled the data at 0.25 millisecond (ms) intervals and recorded the data to 9-track tape.

3.1 BOREHOLE 44792 VERTICAL SEISMIC PROFILE LAYOUT

Borehole 44792 was drilled to a total depth of 174 ft. Four inch polyvinyl chloride (PVC) casing was installed to a depth of 22 ft. This well is located on seismic Line WIN-1 near Shotpoint 250.

The VSP data were acquired using a source location approximately 45 ft northwest of the borehole. The downhole geophone was lowered to 172 ft and 43 levels were recorded up the borehole to a depth of 4 ft. The average depth interval was 4 ft.

A Bolt Air Gun was used for the seismic source. The source was placed in a mudpit prior to detonation. A signature geophone was placed at the surface 2 ft from the source location.

3.2 BOREHOLE 42392 VERTICAL SEISMIC PROFILE LAYOUT

Borehole 42392 was drilled to a total depth of 216 ft. Four inch PVC casing was installed from the surface to 109 ft. This borehole is located in the West Spray Field on seismic Line WSF-1.

The VSP data were acquired using a source location 60 ft east of the borehole. The downhole geophone was lowered to a depth of 197 ft and 66 levels were recorded up to a depth of 59 ft. The average depth interval was 2 ft.

A Bolt Air Gun was used for the seismic source. The air gun was suspended in a water filled 55 gallon drum. To ensure good ground coupling of the source, the drum was placed in an excavation so that approximately 1 ft of the drum was below ground surface. A signature geophone was placed on the ground 3 ft from the source location.

3.3 BOREHOLE 42292 VERTICAL SEISMIC PROFILE LAYOUT

Borehole 42292 was drilled to a total depth of 175 ft. Four inch PVC casing was set to a depth of 34 ft. This well is located near the landfill away from HR seismic lines.

The VSP data were acquired using a source location 36 ft northwest of the borehole. The downhole geophone was lowered to 170 ft and 65 levels were recorded up the borehole to a depth of 24 ft. The average depth interval was 2 ft.

A Bolt Air Gun was used for the seismic source. The source was placed in a mudpit prior to detonation. A signature geophone was placed at the surface 2 ft from the source location to record the source signature and correct for variation in downhole arrival times.

3.4 BOREHOLE 40591 VERTICAL SEISMIC PROFILE LAYOUT

Borehole 40591 was drilled to a total depth of 185 ft. Four inch PVC casing was set to a depth of 14 ft. This well is located approximately 150 ft south of the end of Line WIN-7.

The VSP data were acquired using a source location 33 ft north of the borehole location. The downhole geophone was lowered to 179 ft and 88 levels were recorded up the borehole to a depth of 5 ft. The average interval was 2 ft.

A Bolt Air Gun was used for the seismic source. The air gun was suspended in a water filled 55 gallon drum. The drum was placed into an excavation so that approximately 1 ft of the drum was below ground surface. Three signature geophones were placed on the ground surface 2 ft away from the source location to record the source signature and to correct for variation in downhole arrival times.

4.0 DATA PROCESSING

The specific VSP processing sequence selected for a set of data depends upon the objectives of the VSP program. Many VSP processing techniques have been adapted from surface seismic processing routines. These routines must often be modified to accommodate them to the unique recording parameters associated with VSPs.

A VSP processing sequence was selected to enhance upgoing (reflected) events on the VSP data. These upgoing events may be correlated with the HR seismic reflection profile and borehole synthetic seismogram to allow a more accurate interpretation of the actual depth of a reflector. The basic VSP processing sequence is outlined below:

- Trace editing
- Shot static correction
- Source signature deconvolution
- First break picking
- Wavefield separation (downgoing and upgoing)
- Upgoing static application to two-way time
- Band pass filtering (frequency domain)
- Deconvolution of upgoing (designed on downgoing)
- Upgoing spherical divergence correction
- Corridor stack of upgoing wavefield
- Comparison with HR seismic profile and synthetic seismogram

5.0 DATA ANALYSIS AND INTERPRETATION

In general, the VSP data for each well underwent the above processing sequence and the following plots of the data were generated for interpretation purposes:

- Edited field data
- Downward traveling waves
- Upward traveling waves
- Velocity versus depth curves

Wells 44792 and 42392 are located near HR seismic reflection lines. The VSP data from these wells are presented with the HR seismic reflection data, the lithologic logs, and the borehole sonic and density geophysical logs. Wells 42292 and 40591 are not located near HR seismic reflection lines and are presented with only lithologic logs and borehole sonic and density geophysical logs.

5.1 BOREHOLE 44792

The edited field data, the downward traveling waves, the upward traveling waves, and the velocity versus depth curves for Borehole 44792 are shown in Figures IV-2, IV-3, IV-4, and IV-5, respectively.

The composite display for Borehole 44792 is shown in Figure IV-6. The synthetic seismogram represents the depth interval of 90 to 167 ft. The synthetic seismogram and VSP correlate well with the seismic data from Line WIN-1. The synthetic seismogram, VSP, and seismic profile show a positive amplitude event at 68 ms and at 73 ms. These events are caused by a siltstone at 141 ft and a sandstone at 156 ft.

5.2 BOREHOLE 42392

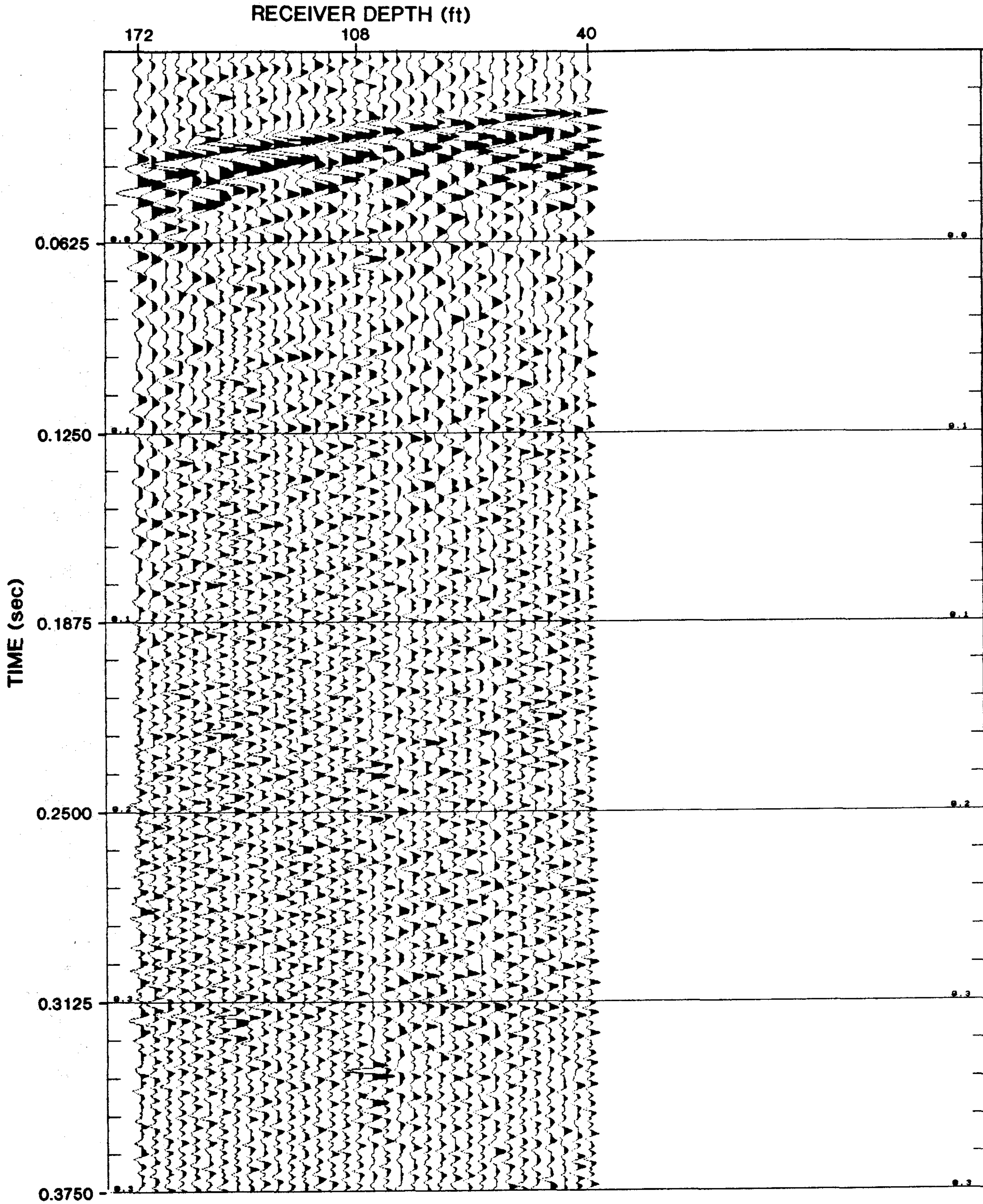
The edited field data, the downward traveling waves, the upward traveling waves, and the velocity versus depth curves for Borehole 42392 are shown in Figures IV-7, IV-8, IV-9, and IV-10, respectively.

The composite display for Borehole 42392 is shown in Figure IV-11. The synthetic seismogram represents the depth interval of 80 to 192 ft. The synthetic seismogram and VSP correlate well with the seismic data from Line WSF-1. The positive, high amplitude event at 65 ms on the synthetic seismogram, VSP, and seismic profile are caused by the bedrock at 100 ft. The other reflections apparent on the synthetic seismogram and VSP are most likely caused by gradational changes in the relative percentages of sand, silt, and clay.

5.3 BOREHOLE 42292

The edited field data, the downward traveling waves, the upward traveling waves, and the velocity versus depth curves for Borehole 42292 are shown in Figures IV-12, IV-13, IV-14, and IV-15, respectively.

The composite display for Borehole 42292 is shown in Figure IV-16. The lithologic log for this borehole shows that claystone and silty claystone were encountered during drilling. The

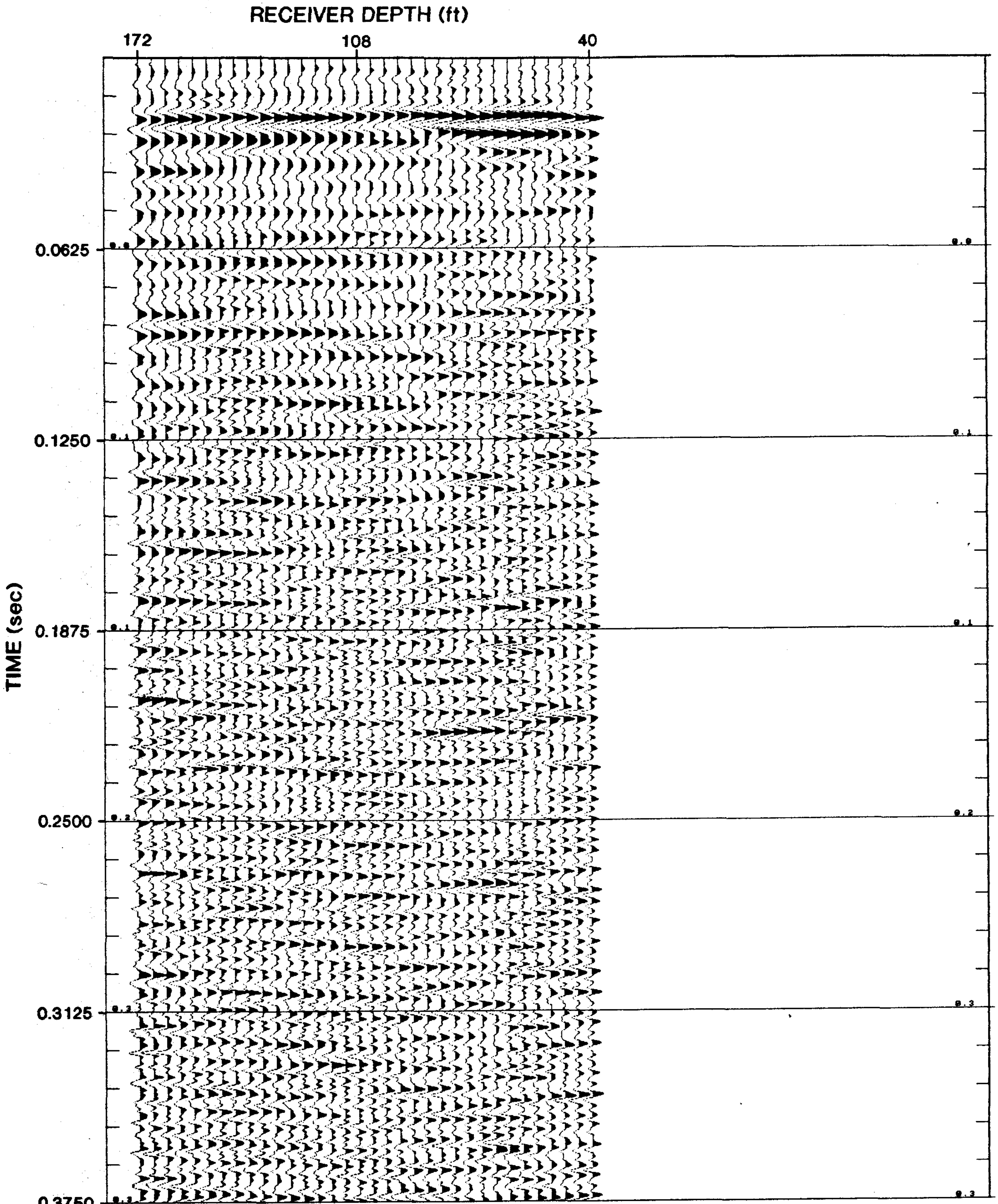


EG & G

ROCKY FLATS PLANT

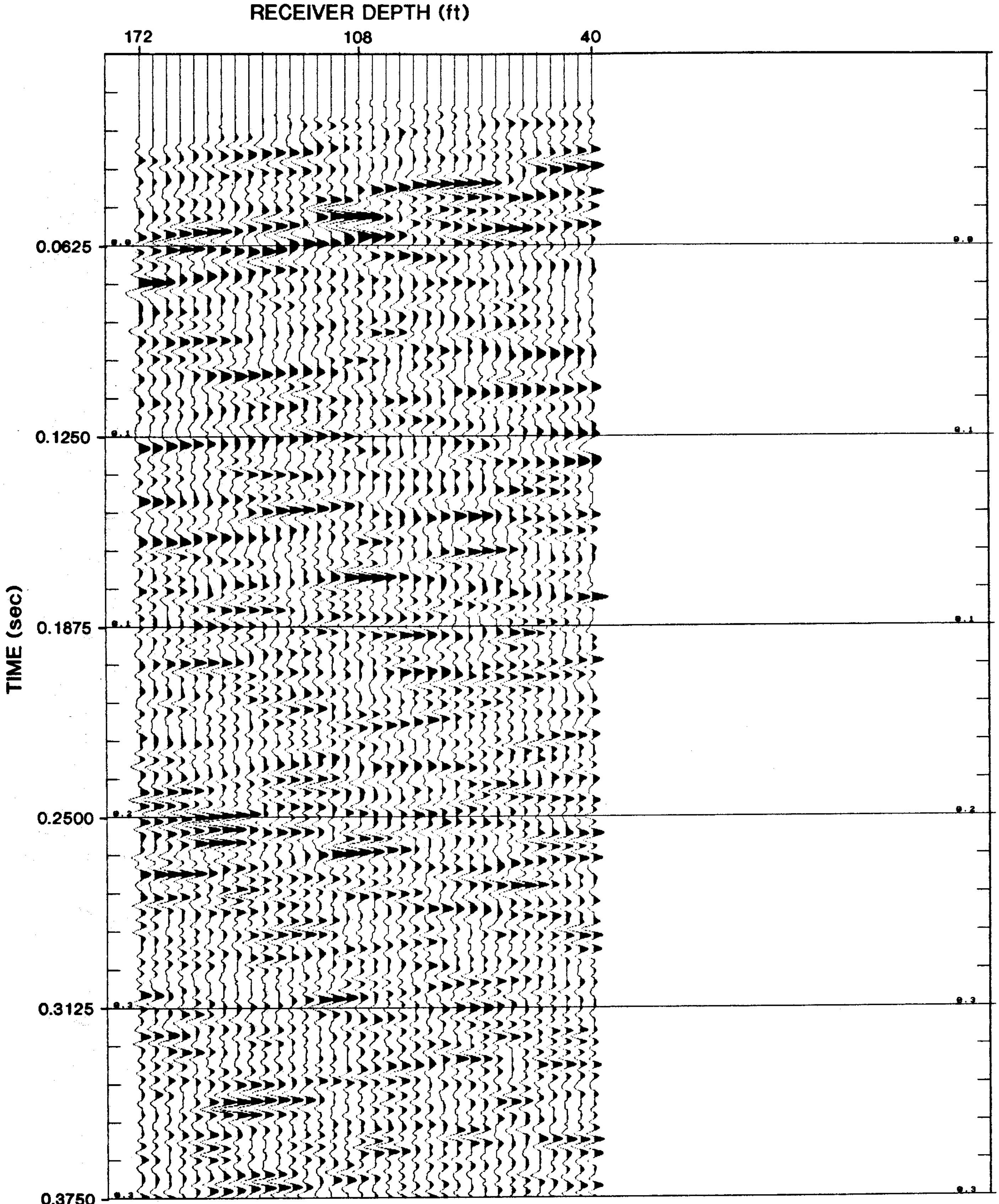
FIGURE IV-2

BOREHOLE 44792 VSP
EDITED FIELD DATA



EG & G
ROCKY FLATS PLANT

FIGURE IV-3
BOREHOLE 44792 VSP
DOWNWARD TRAVELING WAVES

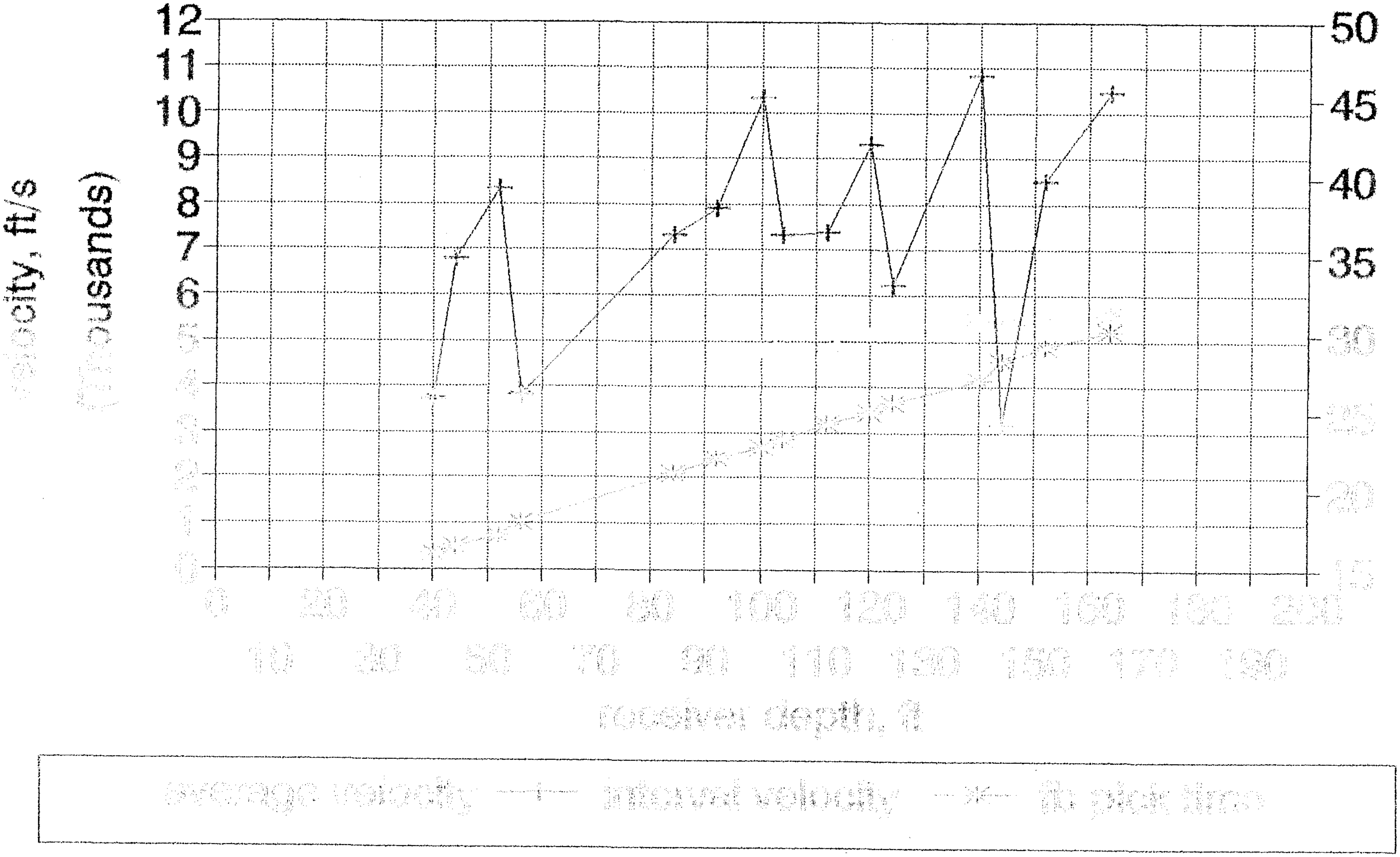


EG & G

ROCKY FLATS PLANT

FIGURE IV-4

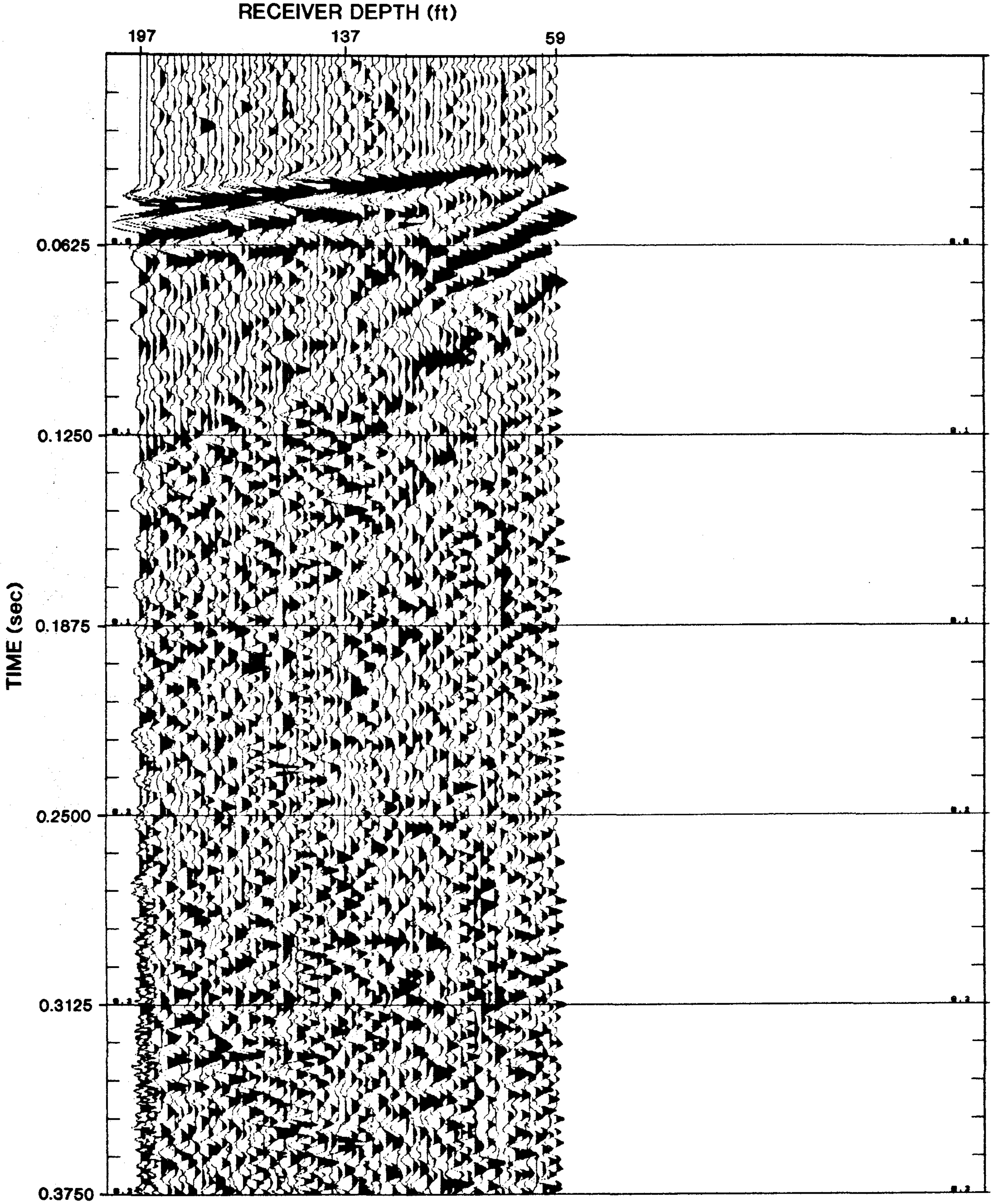
BOREHOLE 44792 VSP
UPWARD TRAVELING WAVES



EG & G
ROCKY FLATS PLANT

FIGURE IV-5

BOREHOLE 44792
VSP VELOCITY VERSUS
DEPTH CURVES



EG & G
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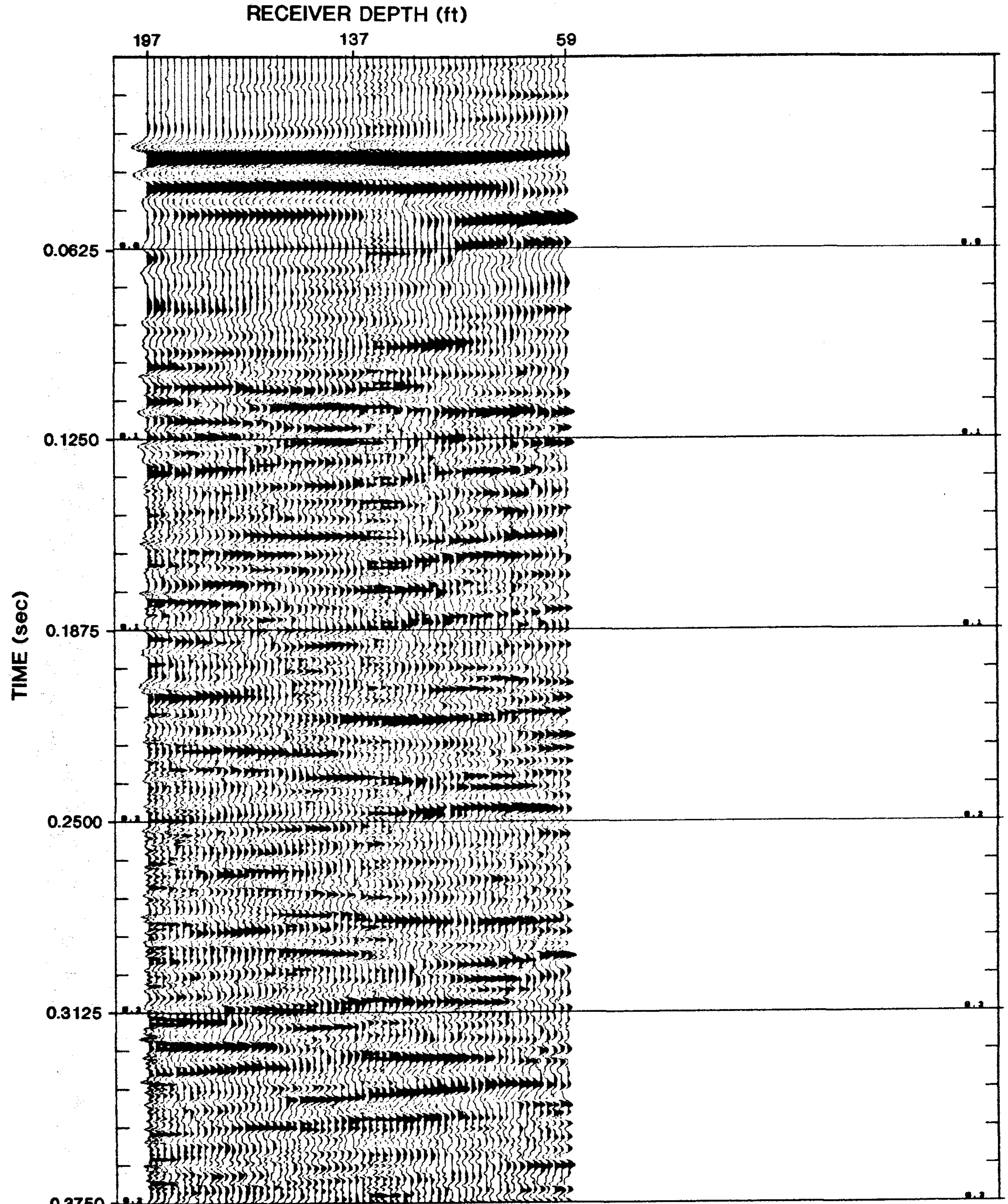
FIGURE IV-7

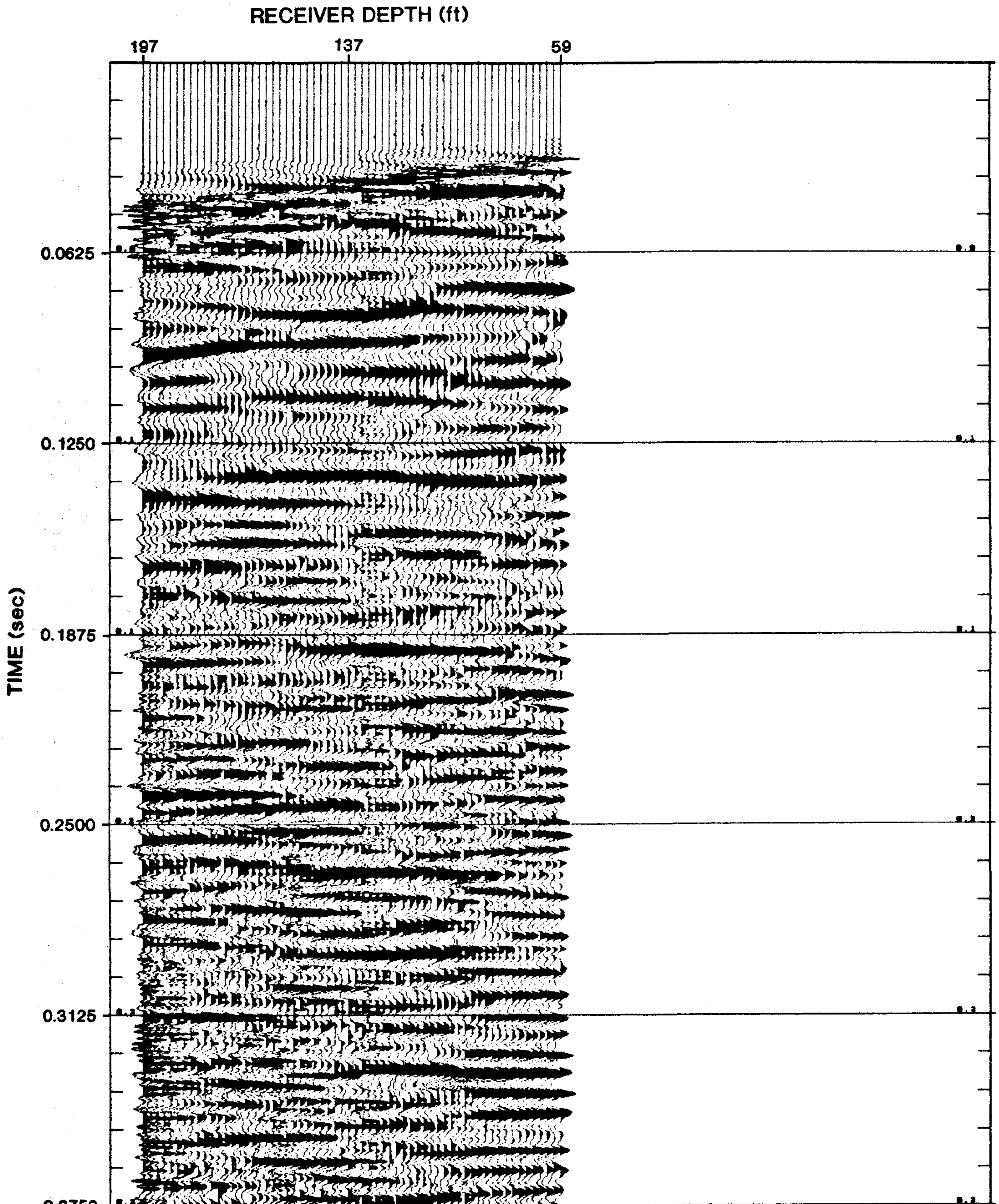
BOREHOLE 42392 VSP
EDITED FIELD DATA



EG & G
ROCKY FLATS PLANT

FIGURE IV-8

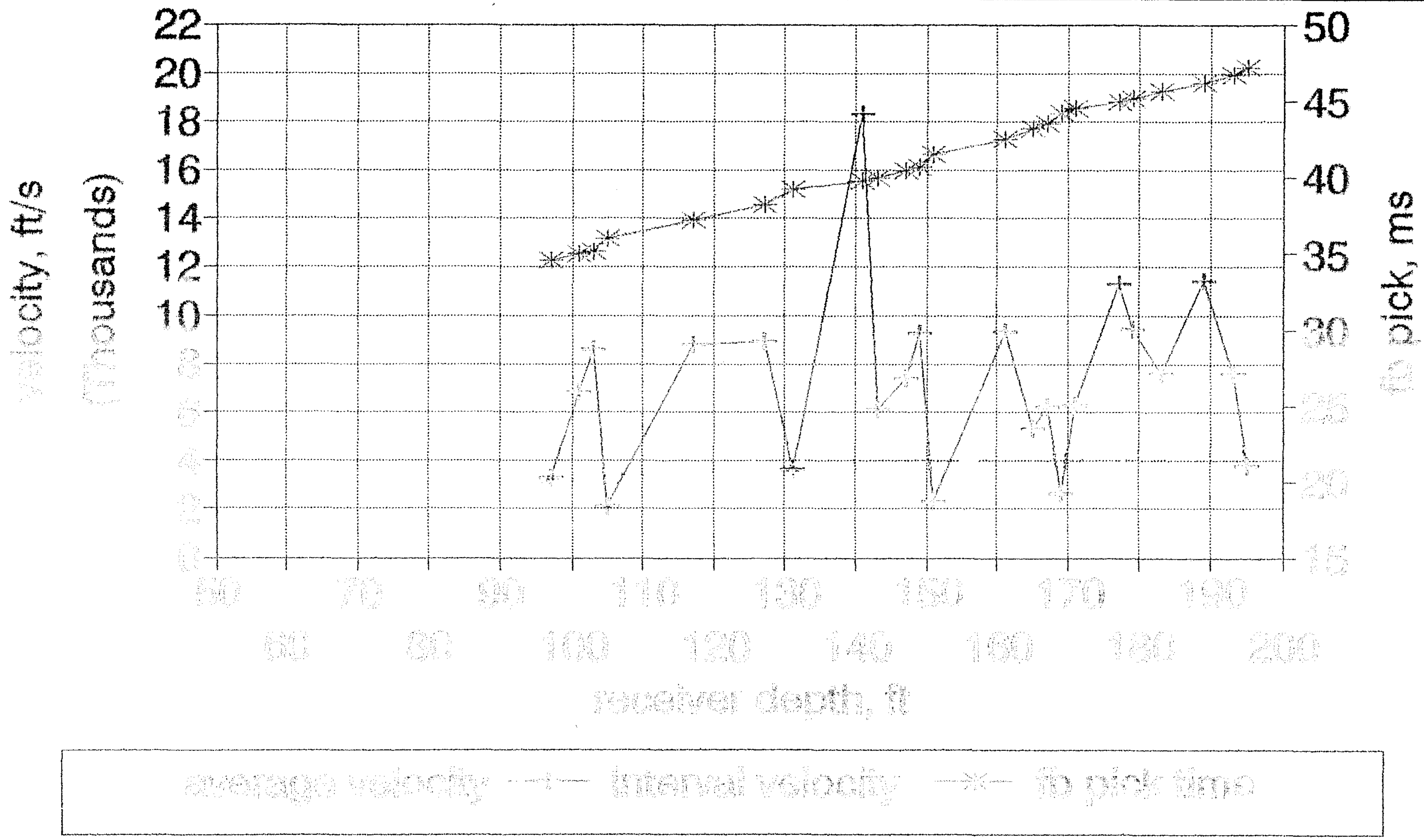
BOREHOLE 42392 VSP
DOWNWARD TRAVELING WAVES



EG & G
ROCKY FLATS PLANT

FIGURE IV-9

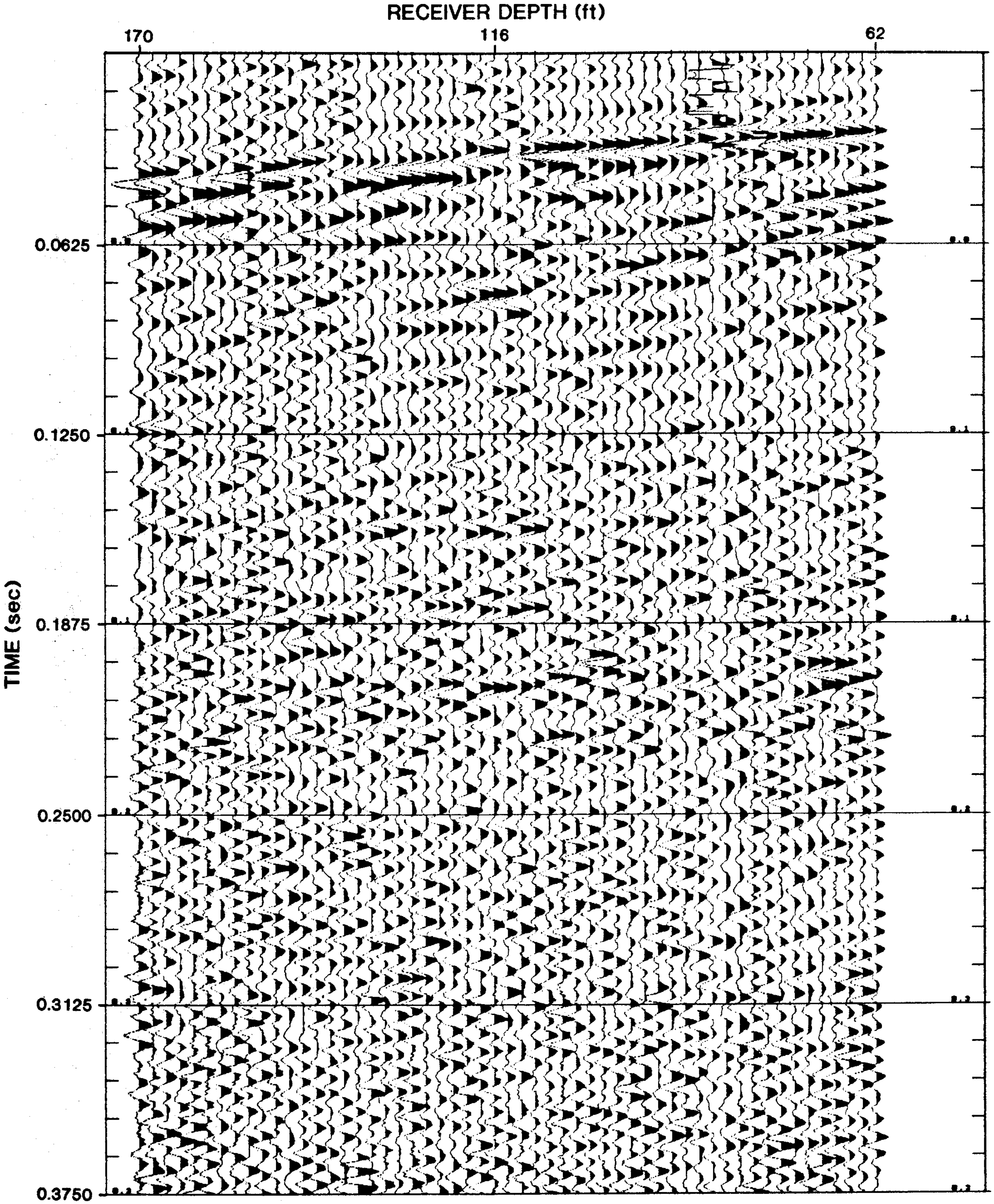
BOREHOLE 42392 VSP
UPWARD TRAVELING WAVES



EG & G
ROCKY FLATS PLANT

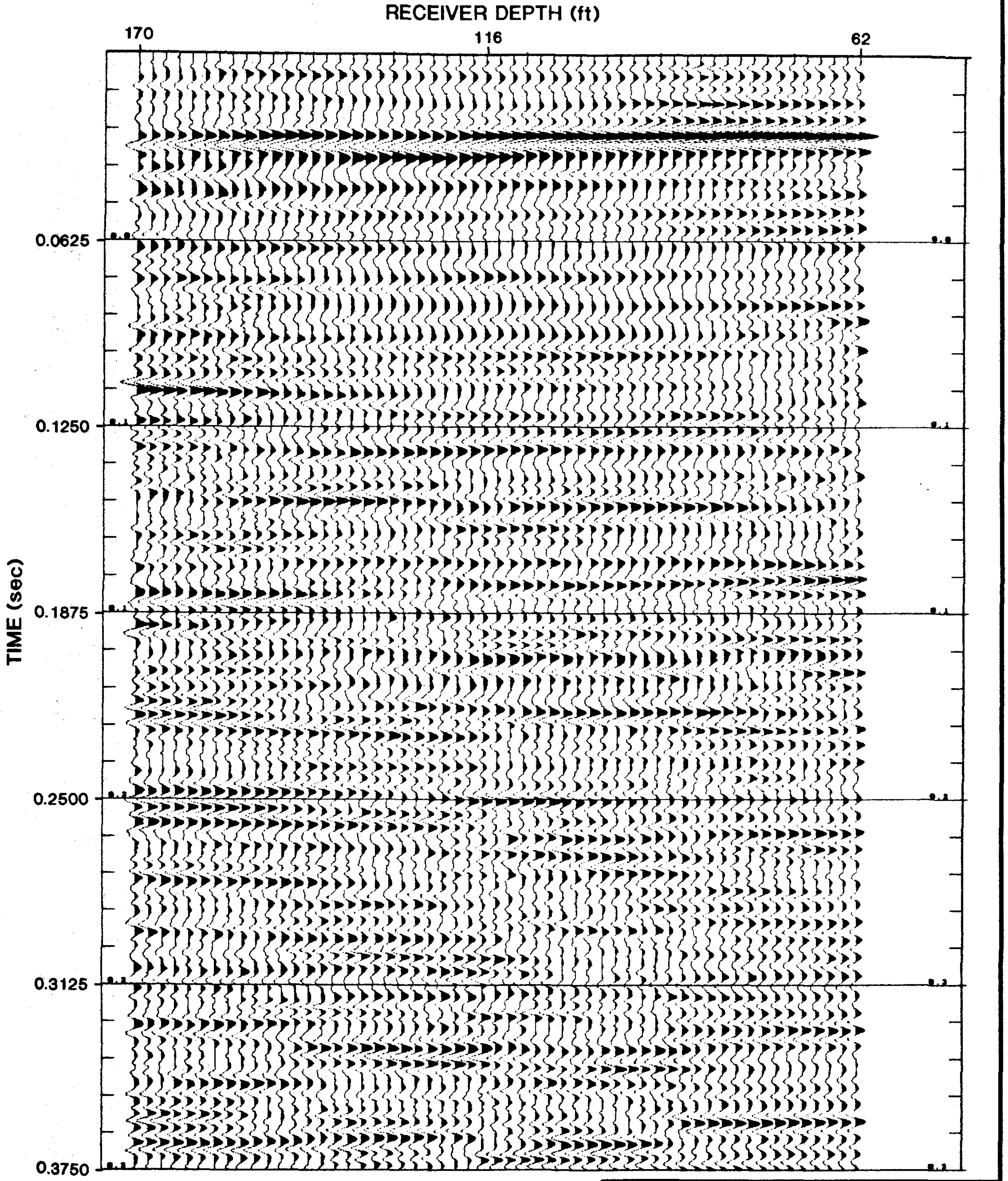
FIGURE IV-10

BOREHOLE 42392
VSP VELOCITY VERSUS
DEPTH CURVES



EG & G
ROCKY FLATS PLANT

FIGURE IV-12
BOREHOLE 42292 VSP
EDITED FIELD DATA



EG & G
ROCKY FLATS PLANT

FIGURE IV-13

BOREHOLE 42292 VSP
DOWNWARD TRAVELING WAVES

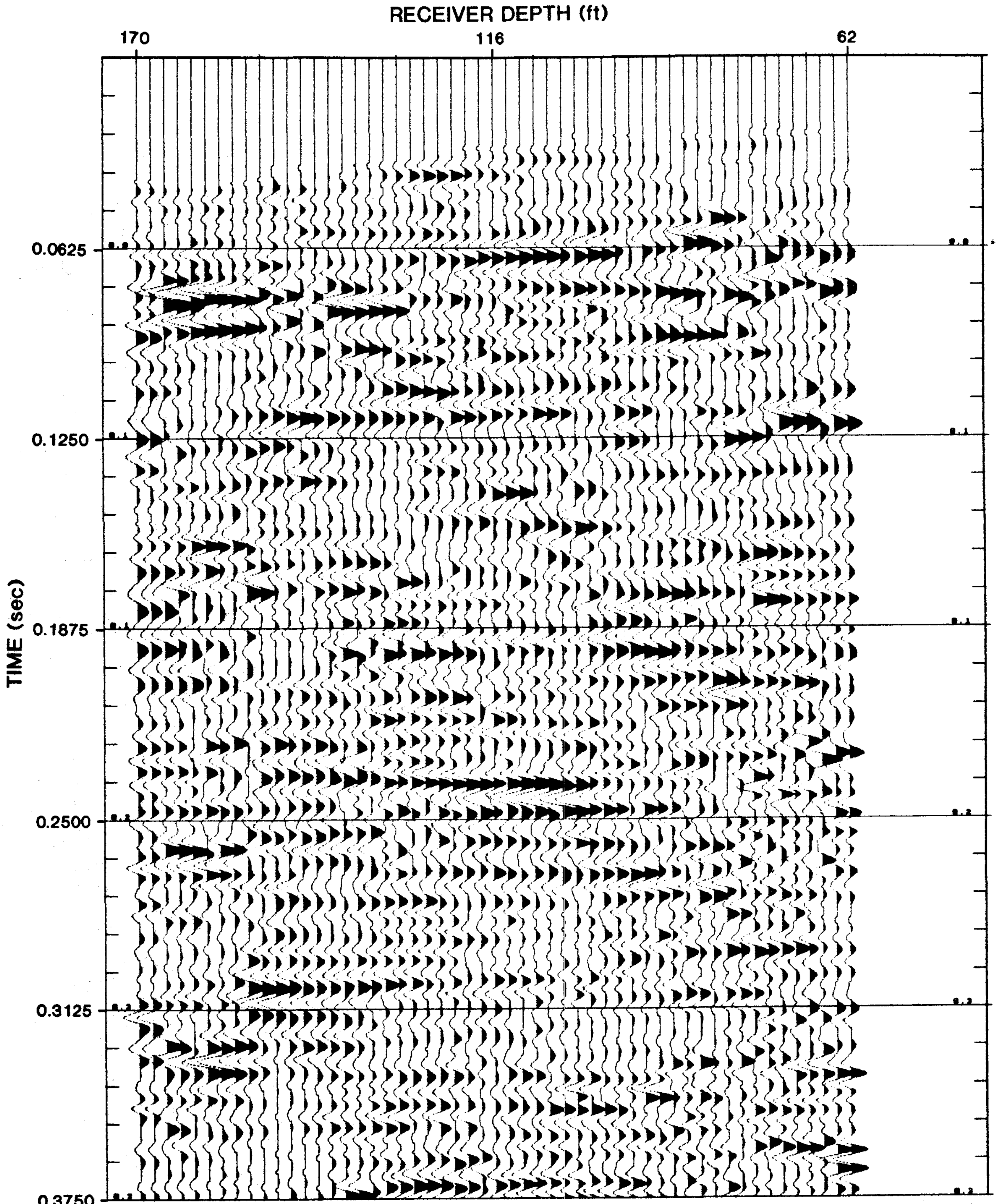


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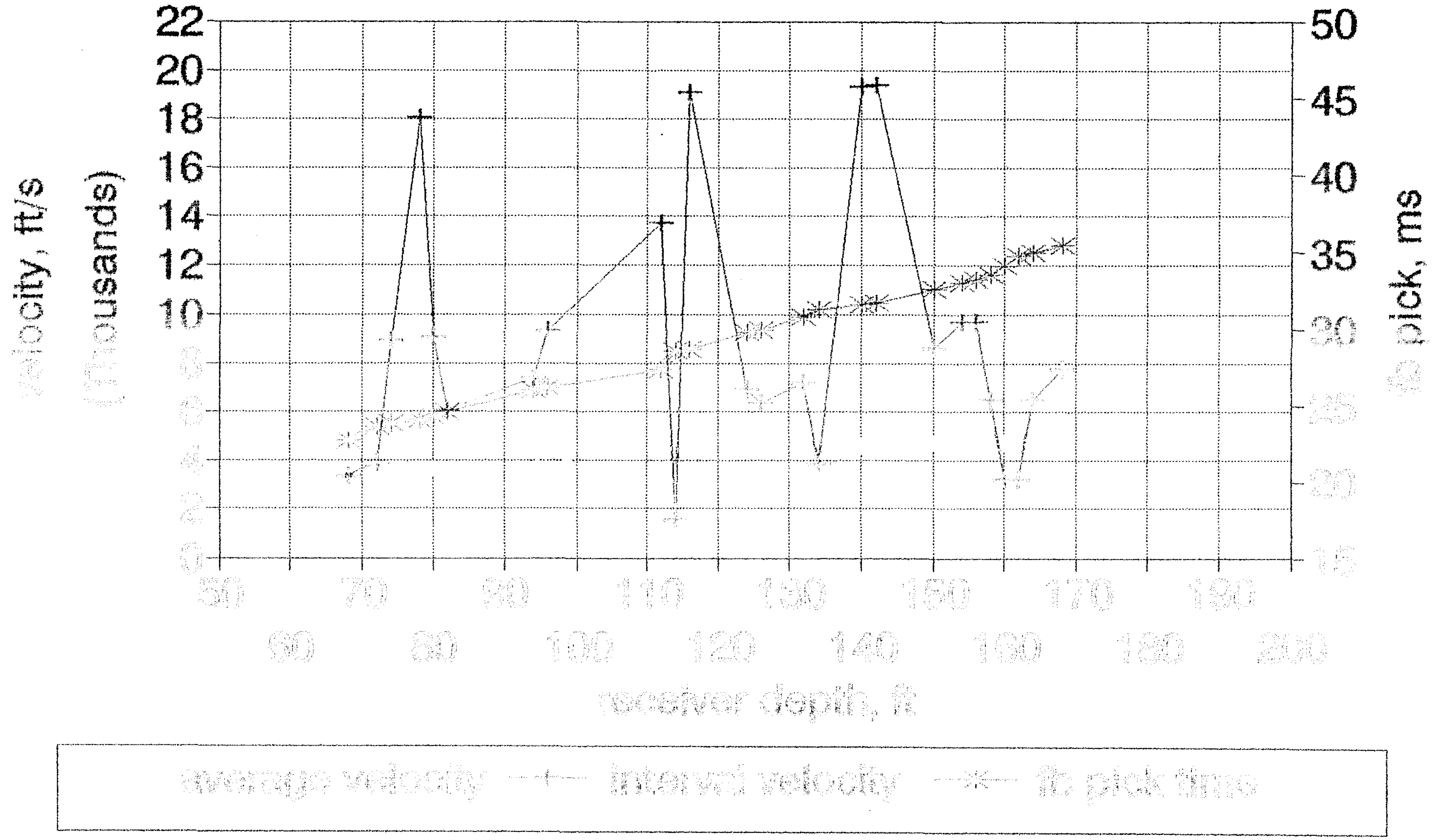
FIGURE IV-14

BOREHOLE 42292 VSP
UPWARD TRAVELING WAVES



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ROCKY FLATS PLANT

FIGURE IV-15

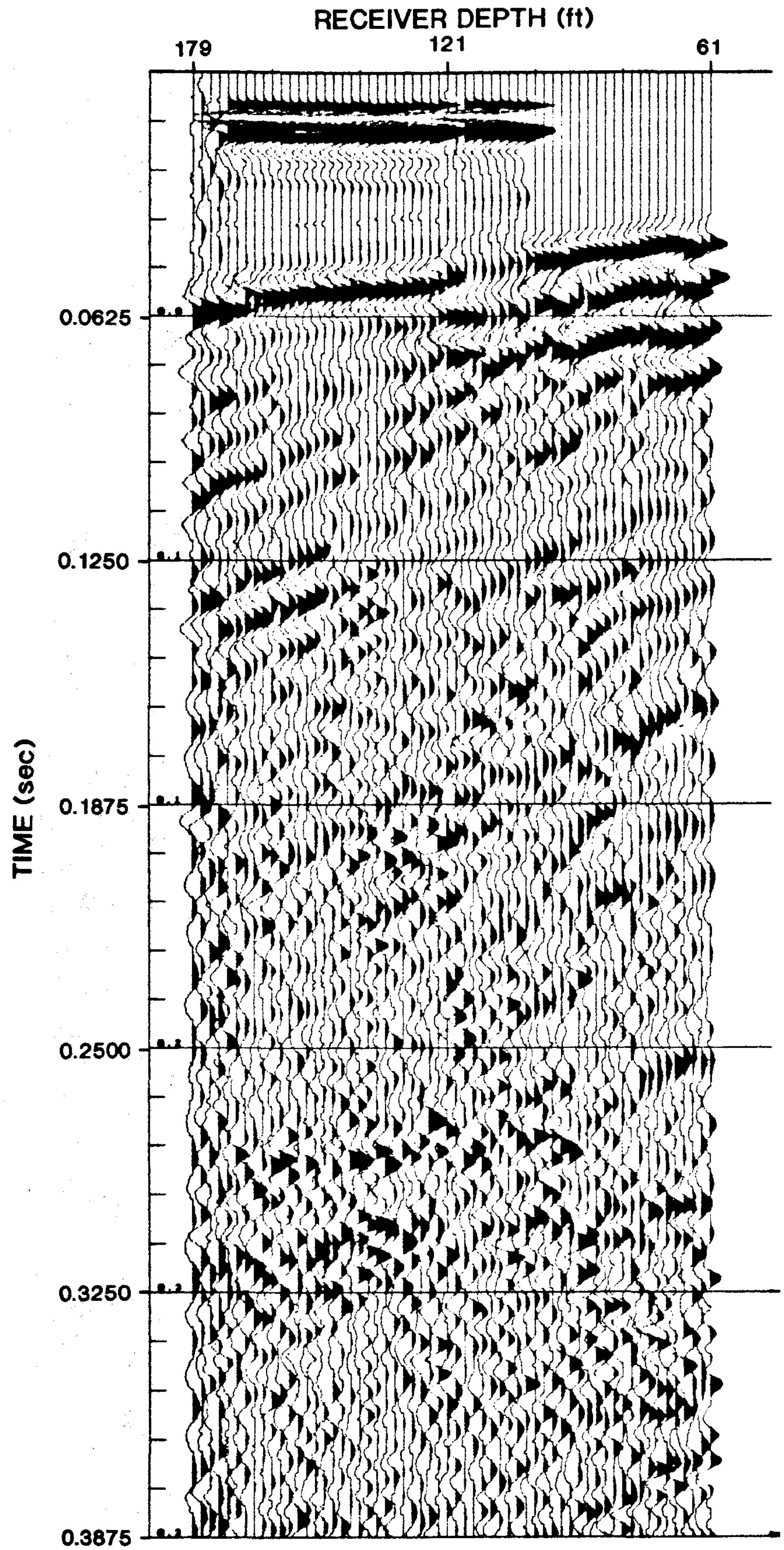
BOREHOLE 42292
VSP VELOCITY VERSUS
DEPTH CURVES

reflections shown on the VSP and the synthetic seismogram are due to the density contrasts between the claystone and the silty claystone in this borehole.

5.4 BOREHOLE 40591

The edited field data, the downward traveling waves, the upward traveling waves, and the velocity versus depth curves for Borehole 40591 are shown in Figures IV-17, IV-18, IV-19, and IV-20, respectively.

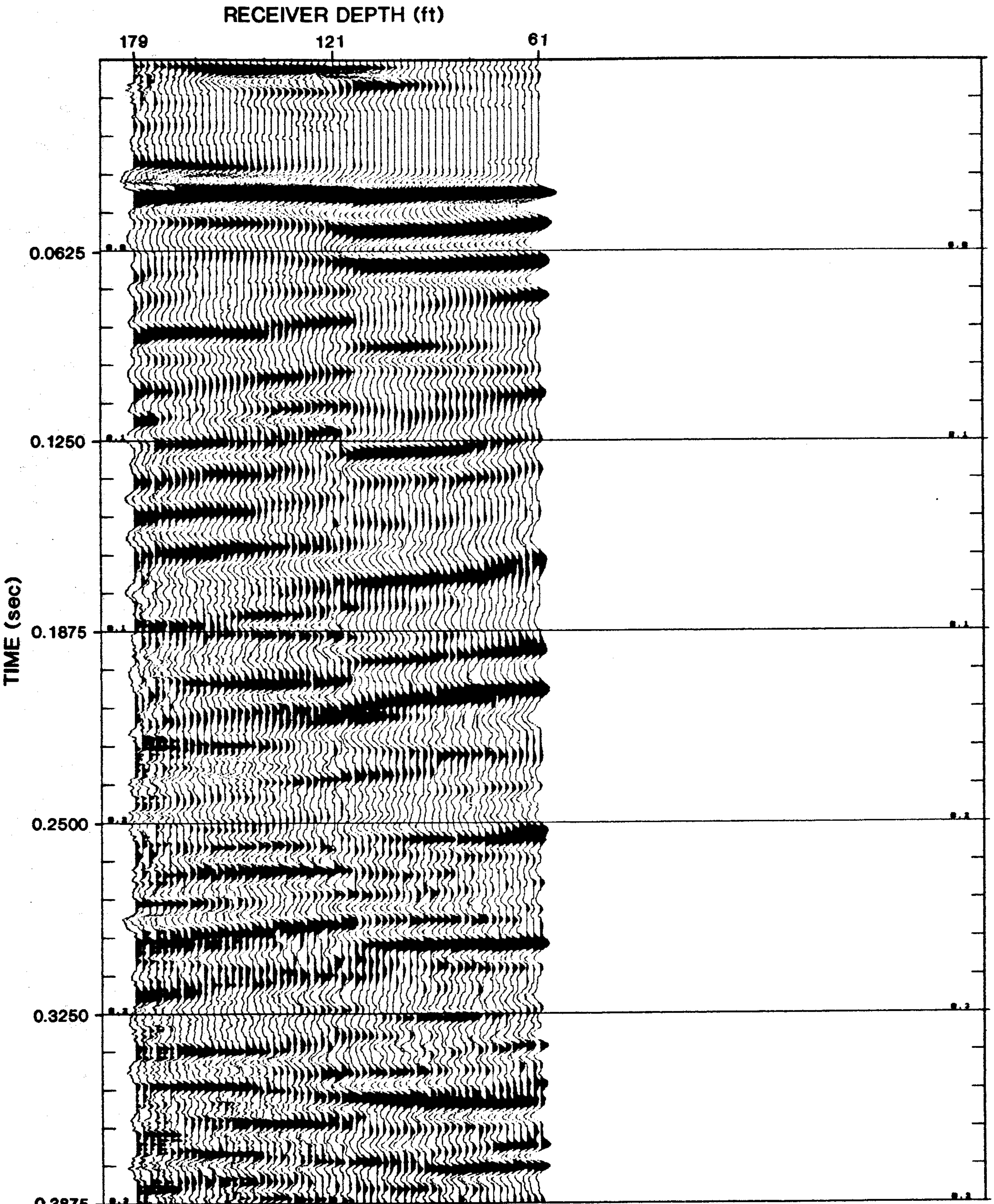
The composite display for Borehole 40591 is shown in Figure IV-21. The lithologic log for this borehole shows a clayey sandstone at 124.5 ft grading into a sandstone from 127 to 130 ft. A negative amplitude event (trough) on the VSP and the synthetic seismogram at 112 ms corresponds to this sandstone interval. The density contrast of the sandstone interval with the underlying claystone (approximately 130 ft) forms a positive amplitude event (peak) on the VSP and the synthetic seismogram at 117 ms. The density contrast between the clayey sandstone from 145 to 153 ft and the underlying silty claystone create the same trough to peak relationship at 122 ms and 127 ms, respectively. The low velocities associated with the sandstones at 125 ft. and 145 ft. may be due to poor cementation.



EG & G
ROCKY FLATS PLANT

FIGURE IV-17

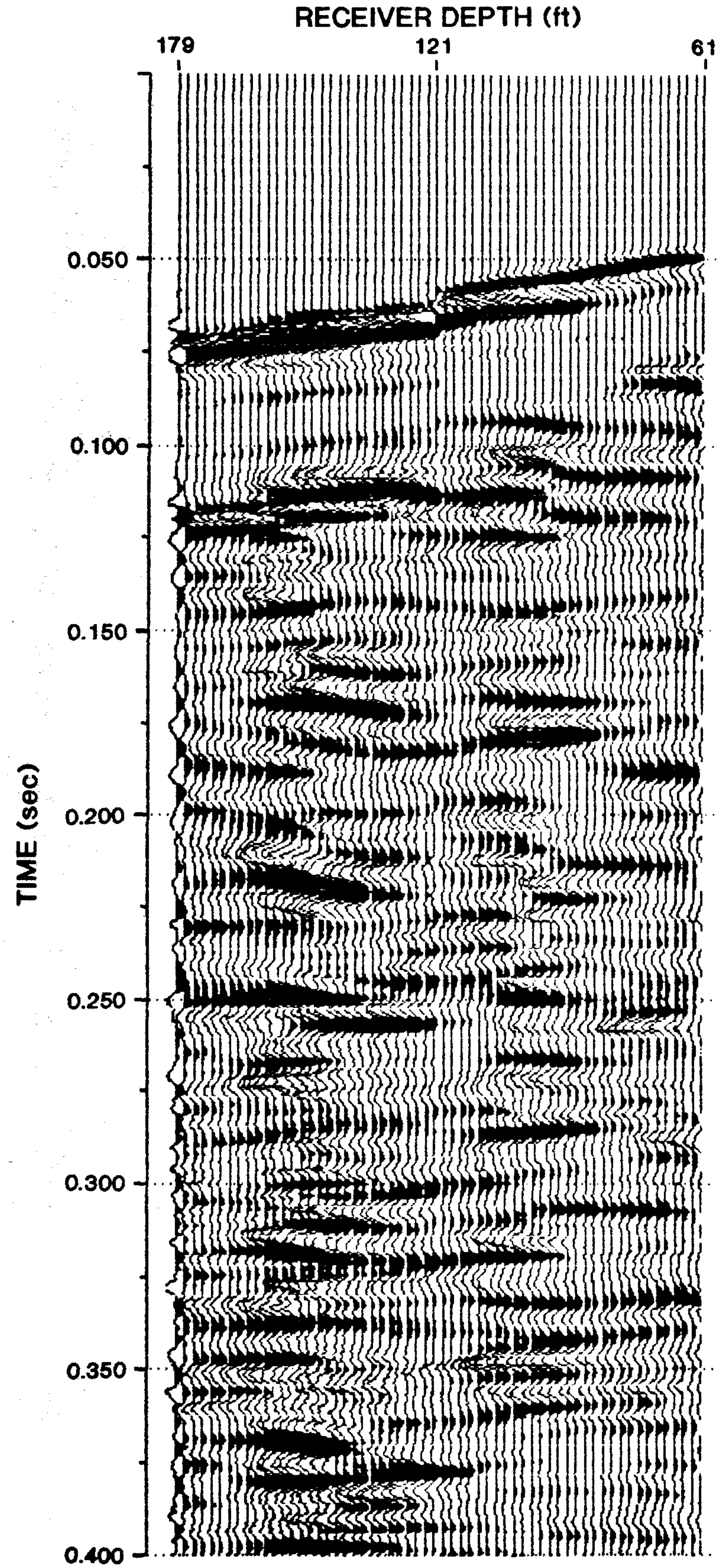
BOREHOLE 40591 VSP
EDITED FIELD DATA



EG & G
ROCKY FLATS PLANT

FIGURE IV-18

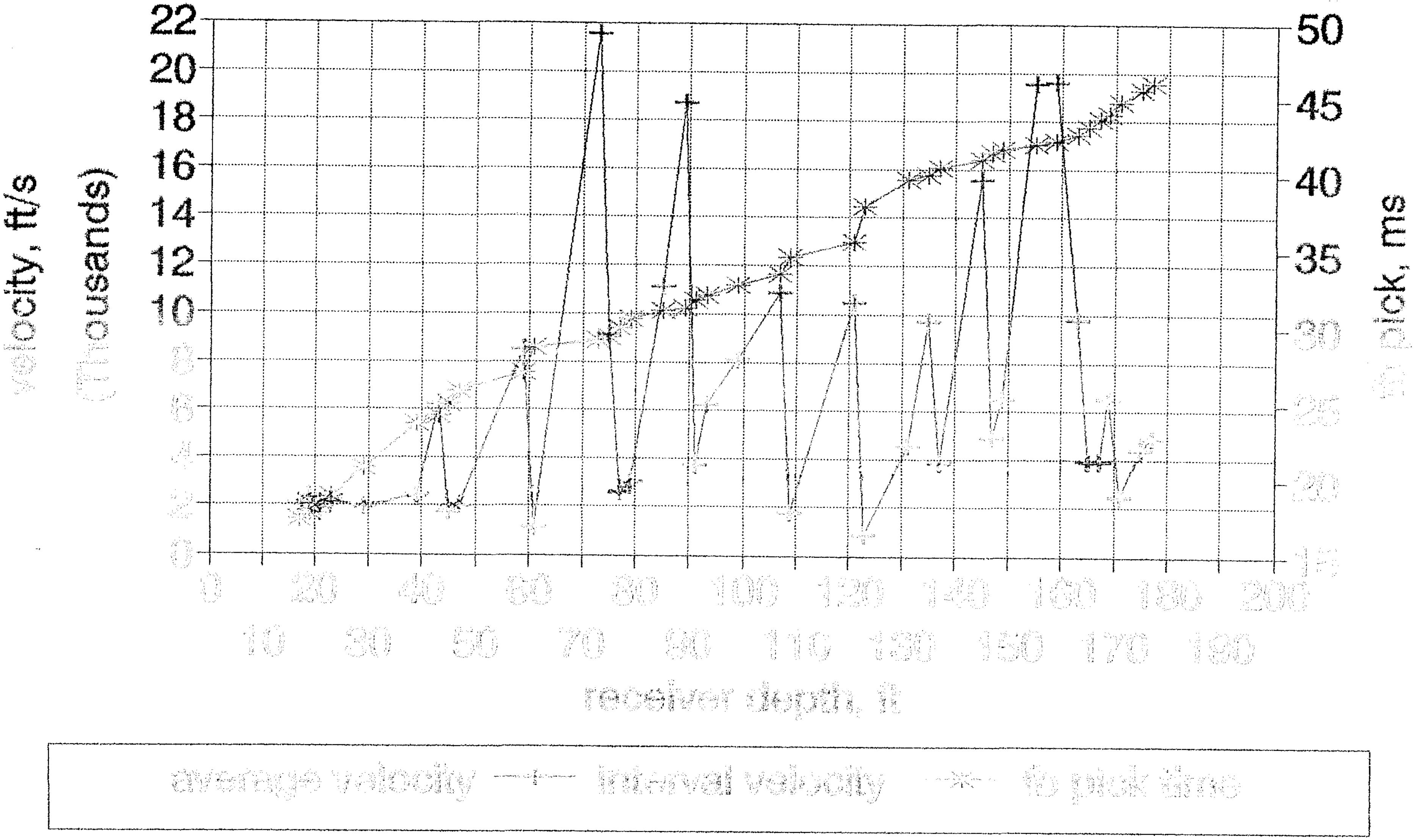
BOREHOLE 40591 VSP
DOWNWARD TRAVELING WAVES



EG & G
ROCKY FLATS PLANT

FIGURE IV-19

BOREHOLE 40591 VSP
UPWARD TRAVELING WAVES



EG & G
ROCKY FLATS PLANT

FIGURE IV–20

BOREHOLE 40591
VSP VELOCITY VERSUS
DEPTH CURVES

Appendix V

Seismic Station Survey Coordinates

Line WIN-1

Station	Northing	Easting	Elevation
101	753083.7	2093847.2	5650.7
125	753131.7	2093847.2	5646.7
150	753181.7	2093847.2	5643.6
156	753193.7	2093847.2	5641.3
159	753199.7	2093847.2	5642.6
169	753219.7	2093847.2	5642.8
175	753231.7	2093847.2	5641.0
200	753281.7	2093847.2	5638.6
225	753331.7	2093847.2	5636.6
250	753381.7	2093847.2	5637.4
275	753431.7	2093847.2	5637.3
300	753481.7	2093847.2	5636.4
320	753521.7	2093847.2	5634.4
322	753525.7	2093847.2	5632.1
324	753529.7	2093847.2	5632.2
326	753533.7	2093847.2	5634.8
350	753581.7	2093847.2	5636.4
375	753631.7	2093847.2	5638.4
400	753681.7	2093847.2	5639.5
425	753731.7	2093847.2	5641.7
450	753781.7	2093847.2	5644.2
475	753831.7	2093847.2	5646.6
498	753877.7	2093847.2	5648.8
500	753881.7	2093847.2	

Line WIN-2

Station	Northing	Easting	Elevation
101	750165.3	2093772.4	5725.4

125	750213.3	2093772.4	5721.2
150	750263.3	2093772.4	5715.1
175	750313.3	2093772.4	5711.3
200	750363.3	2093772.4	5705.2
225	750413.3	2093772.4	5699.9
250	750463.3	2093772.4	5692.9
275	750513.3	2093772.4	5679.9
283	750529.3	2093772.4	5675.7
293	750549.3	2093772.4	5676.3
300	750563.3	2093772.4	5677.5
325	750613.3	2093772.4	5681.3
350	750663.3	2093772.4	5682.1
375	750713.3	2093772.4	5680.8
400	750763.3	2093772.4	5679.5
425	750813.3	2093772.4	5677.6
450	750863.3	2093772.4	5676.7
475	750913.3	2093772.4	5676.9
500	750963.3	2093772.4	5677.4

Line WIN-3

Station	Northing	Easting	Elevation
101	748330.3	2093847.4	5744.4
125	748378.3	2093847.4	5739.9
150	748428.3	2093847.4	5735.1
175	748478.3	2093847.4	5730.8
200	748528.3	2093847.4	5727.2
225	748578.3	2093847.4	5724.6
250	748628.3	2093847.4	5720.7
275	748678.3	2093847.4	5718.0
300	748728.3	2093847.4	5716.8

325	748778.3	2093847.4	5715.9
330	748788.3	2093847.4	5715.6
350	748828.3	2093847.4	5718.1
375	748878.3	2093847.4	5718.1
400	748928.3	2093847.4	5718.3
425	748978.3	2093847.4	5718.8
450	749028.3	2093847.4	5719.6
475	749078.3	2093847.4	5720.5
501	749130.3	2093847.4	5721.4

Line WIN-4

Station	Northing	Easting	Elevation
101	753782.7	2093853.8	5651.6
150	753880.7	2093852.7	5656.7
200	753980.4	2093852.8	5662.5
250	754080.4	2093852.4	5667.1
300	754180.2	2093851.5	5672.7
350	754279.9	2093850.9	5679.2
400	754379.8	2093850.7	5682.4
450	754479.5	2093849.8	5689.8
500	754578.9	2093848.3	5699.6
550	754678.5	2093847.4	5707.3
600	754778.5	2093846.3	5711.4
650	754878.3	2093845.3	5711.0
700	754977.4	2093845.0	5717.8
750	755076.8	2093843.2	5724.3
800	755175.8	2093842.3	5735.1
850	755275.7	2093841.1	5746.0
900	755375.5	2093840.4	5751.7
950	755474.9	2093839.8	5760.4

1000	755573.7	2093838.8	5775.8
1050	755671.4	2093836.9	5797.2
1100	755770.7	2093835.5	5807.5
1150	755870.7	2093835.7	5808.9
1200	755970.6	2093835.4	5812.7
1250	756070.7	2093835.9	5819.8
1300	756170.4	2093835.6	5827.2
1350	756270.1	2093835.3	5836.5
1400	756369.4	2093835.2	5845.3
1450	756469.4	2093833.6	5849.1
1500	756569.5	2093831.2	5849.5
1503	756575.5	2093831.0	5849.5

Line WIN-5

Station	Northing	Easting	Elevation
101	750843.7	2093799.7	5676.2
150	750941.6	2093799.3	5677.4
200	751041.4	2093798.5	5676.3
250	751141.3	2093797.0	5675.4
300	751241.2	2093796.2	5674.3
350	751340.7	2093794.4	5682.4
400	751439.5	2093793.9	5696.5
450	751538.4	2093793.2	5711.4
500	751637.6	2093792.5	5721.7
550	751737.6	2093791.2	5717.5
600	751837.3	2093788.9	5715.2
650	751937.2	2093786.9	5714.1
700	752037.1	2093785.2	5714.8
750	752137.0	2093783.2	5715.0
800	752236.5	2093784.7	5706.5

850	752335.1	2093787.1	5690.1
900	752434.3	2093789.3	5677.9
950	752533.8	2093792.2	5672.9
1000	752633.7	2093794.7	5673.3
1050	752733.8	2093798.1	5675.6
1100	752833.2	2093800.7	5666.8
1150	752933.1	2093803.8	5663.4
1200	753033.2	2093807.6	5662.9
1250	753132.8	2093810.8	5657.9
1275	753182.6	2093811.8	5653.9

Line WIN-6

Station	Northing	Easting	Elevation
101	749359.1	2093784.2	5742.7
150	749456.1	2093783.6	5748.9
200	749556.4	2093783.0	5753.7
250	749656.5	2093782.9	5758.7
300	749756.6	2093782.6	5764.1
350	749856.5	2093781.6	5766.0
400	749954.6	2093780.8	5752.9
450	750053.6	2093779.3	5739.5
500	750152.8	2093777.5	5729.0
547	750245.4	2093775.6	5717.8

Line WIN-7

Station	Northing	Easting	Elevation
101	748394.8	2093925.0	5742.0
150	748297.2	2093925.5	5751.3
200	748198.1	2093926.1	5763.1
250	748098.4	2093926.6	5770.6

253	748092.5	2093926.6	5770.8

Appendix VI
Glossary of Geophysical Terms

GLOSSARY

A selection of relevant geophysical terms extracted from
Encyclopedic Dictionary of Exploration Geophysics (Sheriff, 1984),
Applied Geophysics (Telford et al., 1976),
Geophysical Prospecting (Dobrin, 1976; Dobrin and Savit, 1988).

ACCELEROMETER - A geophone whose output is proportional to the acceleration of earth particles. For example, a moving coil geophone, with velocity response proportional to frequency (as may be the case below the natural frequency) operates as an accelerometer.

ACOUSTIC - IMPEDANCE - Seismic velocity multiplied by density. Reflection coefficient at normal incidence depends on changes in acoustic impedance.

ACOUSTIC LOGGING - A borehole logging survey which will display any of several aspects of seismic-wave propagation, i.e., a sonic, amplitude, character or 3D-log.

AIR WAVE - Energy from the shot which travels in the air at the velocity of sound: V = 1051 + 1.1F ft/s, where F = Fahrenheit temperature, or V = 331.5 + 0.607C m/s, where C = Celsius temperature.

ALIAS - Data in sampled form have an ambiguity where there are fewer than two samples per cycle. This creates a situation where an input signal at one frequency appears to have another frequency at the output of the system. Half of the frequency of sampling is called the folding or Nyquist frequency, f_N, and a frequency larger than this, $f_N + Y$, appears to have the smaller frequency f_N-Y. To avoid this ambiguity, frequencies above the Nyquist frequency must be removed by an anti-alias filter before the sampling. Otherwise the system will react as if the spectral characteristics were folded back at the Nyquist frequency. Thus, for a system sampled over 4 ms, or 250 times per second, the Nyquist frequency is 125 cps; if, for example, 50 cps is within the pass band, then 200 cps will also be passed if an anti-alias filter is not used, appearing upon output to have a 50 cps frequency. The pass bands obtained by folding about the Nyquist frequency are also called "alias bands," "side lobes," and "secondary lobes." Aliasing is an inherent property of all sampling systems and applies to digital seismic recording and also to the sampling which is done by the separate elements of geophone and shotpoint arrays.

ANALOG - (1) A continuous physical variable (such as voltage or rotation) which bears a direct relationship (usually linear) to another variable (such as earth motion) so that one is proportional to the other. (2) Continuous, as opposed to discrete or digital.

ANOMALY - A deviation from uniformity in physical properties, often of exploration interest. For example, a travel time anomaly, Bouguer anomaly, free-air anomaly.

APPARENT VELOCITY - (1) The phase velocity which a wavefront appears to have along a line of geophones. (2) The inverse of the slope of a time-distance curve.

ATTENUATION - A reduction in amplitude or energy caused by the physical characteristics of the transmitting media or system. Usually includes geometric effects such as the decrease in amplitude of a wave with increasing distance from a source. Also used for instrumental reduction effects such as might be produced by passage through a filter.

AUTOMATIC GAIN CONTROL (AGC) - A system in which the output amplitude is used for automatic control of the gain of a seismic amplifier, usually individual for each channel, although multi-channel devices are sometimes used.

BEDROCK - Any solid rock, such as may be exposed at the surface of the earth or overlain by unconsolidated material.

BODY WAVES - P-waves and S-waves, which travel through the body of a medium, as opposed to surface waves.

CABLE - The assembly of electrical conductors used to connect the geophone groups to the recording instrument.

CAPACITANCE - The ratio of charge (Q in coulombs) on a capacitor to the potential across it (V in volts) is the capacitance (C in farads):

$$C = Q/V$$

CHANNEL - (1) A single series of interconnected devices through which geophysical data can flow from sources to recorder. Most seismic systems are 24 channel, allowing the simultaneous recording of energy from 24 groups of geophones. (2) A localized elongated geological feature resulting from present or past drainage or water action; often presents a weathering problems. (3) An allocated portion of the radio-frequency spectrum.

CHANNEL WAVE - An elastic wave propagated in a layer of lower velocity than those on either side of it. Energy is largely prevented from escaping from the channel because of repeated total reflection at the channel boundaries or because rays which tend to escape are bent back toward the channel by the increasing velocity away from it in either direction.

CHARACTER - (1) The recognizable aspect of a seismic event, usually in the waveform, which distinguishes it from other events. Usually a frequency or phasing effect, often not defined precisely and hence dependent upon subjective judgment. (2) A single letter, numeral, or special symbol in a processing system.

COMMON DEPTH POINT (CDP) - The situation where the same portion of subsurface produces reflections at different offset distances on several profiles.

COMPRESSIONAL WAVE - An elastic body wave in which particle motion is in the direction of propagation. (Same as P-waves, longitudinal wave, dilation wave).

CONVERTED WAVE - A wave which is converted from longitudinal to transverse, or vice versa, upon reflection or refraction at oblique incidence from an interface.

CRITICAL ANGLE - Angle of incidence, q_c, for which the refracted ray grazes the surface of contact between two media (of velocities V_1 and V_2):

$$\sin q_c = V_1/V_2$$

CRITICAL DISTANCE - (1) The offset at which the reflection time equals the refraction time; that is, the offset for which the reflection occurs at the critical angle (see Sheriff, 1984 p. 45). (2) Sometimes incorrectly used for crossover distance, the offset at which a refracted event becomes the first break.

CROSSFEED - Interference resulting from the unintentional pickup of information or noise on one channel from another channel. Also crosstalk.

CROSS-HOLE METHOD - Technique for measuring in situ compressional (p) and/or shear (s) wave velocities by recording transit times from a source within one borehole to receivers at the same elevation in one or more other boreholes. Sources may be explosive or directional to enhance either P- or S-wave generation.

CROSS SECTION - A plot of seismic events.

DATUM - (1) The arbitrary reference level to which measurements are corrected. (2) The surface from which seismic reflection times or depths are counted, corrections having been made for local topographic and/or weathering variations. (3) The reference level for elevation measurements, often sea level.

DELAY TIME - (1) In refraction work, the additional time required for a wave to follow a trajectory to and along a buried marker over that which would have been required to follow the same marker considered hypothetically to be at the ground surface or at a reference level. Normally, delay time exists separately under a source and under a detector; and is dependent upon the depth of the marker at wave incidence and emergence points. Shot delay time plus geophone delay time equals intercept time (See Dobrin, 1988 p. 472). (2) Delay produced by a filter.

DIELECTRIC CONSTANT - A measure of the capacity of a material to store charge when an electric field is applied. It is the dimensionless ratio of the capacitivity (or permittivity, the ratio of the electrical displacement to the electric field strength) of the material to that of free space.

DIFFRACTION - (1) Scattered energy which emanates from an abrupt irregularity of rock type, particularly common where faults cut reflecting interfaces. The diffracted energy shows greater curvature than a reflection (except in certain cases where there are buried foci), although not necessarily as much as the curve of maximum convexity. It frequently blends with a reflection and obscures the fault location or becomes confused with dip. (2) Interference produced by scattering at edges. (3) The phenomenon by which energy is transmitted laterally along a wave crest. When a portion of a wave train is interrupted by a barrier, diffraction allows waves to propagate into the region of the barrier's geometric shadow.

DIGITAL -	Representation of quantities in discrete units. A digital system is one in which the information is contained and manipulated as a series of discrete numbers as opposed to an analog system, in which the information is represented by a continuous flow of the quantity constituting the signal.
DOWN-HOLE METHOD -	Technique for measurement of in situ compressional and shear wave velocities utilizing a seismic source at ground surface and a clamped triaxial geophone at depth in a borehole. Shear wave energy is often enhanced by use of directional sources such as striking the ends of a weighted plank.
END LINE -	Shotpoints that are shot near the end of the spread.
FIRST BREAK -	The first recorded signal attributable to seismic wave travel from a known source. First breaks on reflection records are used for information about the weathering. Refraction work is based principally on the first breaks, although secondary (later) refraction arrivals are also used. Also first arrival.
FOLD -	The multiplicity of common-midpoint data. Where the midpoint is the same for 12 offset distances, e.g., the stack is referred to as "12-fold".
FREQUENCY DOMAIN -	A representation in which frequency is the independent variable; the Fourier transform variable when transforming from time.
GAIN -	An increase (or change) in signal amplitude (or power) from one point in a circuit or system to another, often from system input to output.
GALVANOMETER -	A part of a seismic camera consisting of a coil suspended in a constant magnetic field. The coil rotates through an angle proportional to the electrical current flowing through the coil. A small mirror on the coil reflects a light beam, which exhibits a visual record of the galvanometer rotation.
GEOPHONE -	The instrument used to convert seismic energy into electrical voltage. Same as seismometer.
GEOPHONE STATION -	Point of location of a geophone on a spread, expressed in engineering notation as 1+75 taken from 0+00 at the beginning of the line.

GROUP VELOCITY - The velocity with which most of the energy in a wave train travels. In dispersive media where velocity varies with frequency, the wave train changes shape as it progresses so that individual wave crests appear to travel at a different velocity (the phase velocity) than the overall energy as approximately enclosed by the envelope of the wave train. The velocity of the envelope is the group velocity. Same as dispersion.

HYDROPHONE - (Pressure detector) A detector which is sensitive to variations in pressure, as opposed to a geophone which is sensitive to particle motion. Used when the detector can be placed below a few feet of water, as in marine or marsh or as a well seismometer. The frequency response of the hydrophone depends on its depth beneath the surface.

IMBRICATE FAULTING - A series of nearly parallel and overlapping minor thrust faults, high angle reverse faults, or slides, and characterized by rock slices, sheets, plates, blocks, or wedges that are approximately equidistant and have the same displacement and that are all steeply inclined in the same direction (toward the source of stress).

IMPEDANCE - The apparent resistance to the flow of alternating current, analogous to resistance in a dc circuit. Impedance is (in general) complex, of magnitude Z with a phase angle g. These can be expressed in terms of resistance R (in ohms), inductive reactance $X_L = 2pL$, and capacitive reactance $X_c = 1/2pnC$:

$$Z = [R^2 + (X_L - X_C)^{2]1/2,}$$
$$g = \tan^{-1}[(X_L - X_C)/R].$$

Z is in ohms when frequency n is in hertz, L is inductance in henrys, and C is capacitance in farads.

IN-LINE OFFSET - A spread which is shot from a shotpoint which is separated (offset) from the nearest active point on the spread by an appreciable distance (more than a few hundred feet) along the line of spread.

INPHASE - Electrical signal with the same phase angle as that of the exciting signal or comparison signal.

LEAD - An electrical conductor for connecting electrical devices. Geophones are connected to cables at the takeouts via leads on the geophones.

LINE - A series of profiles shot in line.

LOVE WAVE - A surface seismic channel wave associated with a surface layer which has rigidity, characterized by horizontal motion perpendicular to the direction of propagation with no vertical motion.

LOW-VELOCITY LAYER - A near-surface belt of very low-velocity material often abbreviated LVL; also called weathering.

MAGNETIC PERMEABILITY - The ratio of the magnetic induction B to the inducing field strength H: denoted by the symbol m:

$$m = B/moH$$

mo is the permeability of free space = $4p10^{-7}$ weber/ampere meter or (henrys/meter) in SI system, and 1 gauss/oersted in the cgs system, so that the permeability m is dimensionless. The quantity mmo is sometimes considered the permeability (especially in the cgs system).

MIS-TIE - (1) The time difference obtained on carrying a reflection, phantom, or some other measured quantity around a loop; or the difference of the values at identical points on intersecting lines or loops. (2) In refraction shooting, the time difference from reversed profiles which gives erroneous depth and dip calculations.

MULTIPLE - Seismic energy which has been reflected more than once. Same as long-path multiple, short path multiple, peg-leg multiple, and ghost.

MULTIPLEX - A process which permits transmitting several channels of information over a single channel without crossfeed. Usually different input channels are sampled in sequence at regular intervals and the samples are fed into a single output channel; digital seismic tapes are multiplexed in this way. Multiplexing can also be done by using different carrier frequencies for different information channels and in other ways.

NOISE - (1) Any undesired signal; a disturbance which does not represent any part of a message from a specified source. (2) Sometimes restricted to energy which is random. (3) Seismic energy which is not resolvable as reflections. In this sense noise includes microseisms, shot-generated noise, tape-modulation noise, harmonic distortions, etc. Sometimes divided into coherent noise (including non-reflection coherent events) and random noise (including wind noise, instrument noise, and all other energy which is non-coherent). To the extent that noise is random, it can be attenuated by a factor of n by compositing n signals from independent measurements. (4) Sometimes restricted to seismic energy not derived from the shot explosion. (5) Disturbances in observed data due to more or less random inhomogeneities in surface and near surface material.

NOISE SURVEY - A mapping of ambient, continuous seismic noise levels within a given frequency band. As some geothermal reservoirs are a source of short-period seismic energy, this technique is a useful tool for detecting such reservoirs. Also called ground noise survey.

OBSERVER - The geophysicist in charge of recording and overall field operations on a seismic crew.

ON-LINE - Shotpoints that are shot at any point on a spread other than at the ends of the spread.

OSCILLOGRAPH - An instrument that renders visible a curve representing the time variations of electric phenomena.

OSCILLOSCOPE - A type of oscillograph that visually displays an electrical wave on the screen of a cathode ray tube type.

PERMITTIVITY - Capacitivity (q.v.) of a three-dimensional material, such as a dielectric. Relative permittivity is the dimensionless ratio of the permittivity of a material to that of free space; it is also called the dielectric constant.

PHASE VELOCITY - The velocity with which any given phase (such as a trough or a wave of single frequency) travels; may differ from group velocity because of dispersion.

PLANT - The manner in which a geophone is placed on or in the earth; the coupling to the ground.

PROFILE - The series of measurements made from several shotpoints into a recording spread from which a seismic data cross section or profile can be constructed.

PROFILING - A geophysical survey in which the measuring system is moved about an area (often along a line) with the objective of determining how measurements vary with location. Specifically, a resistivity, IP, or electromagnetic field method wherein a fixed electrode or antenna array is moved progressively along a traverse to create a horizontal profile of the apparent resistivity.

RADAR - A system in which short electromagnetic waves are transmitted and the energy scattered back by reflecting objects is detected. Acronym for "radio detection and ranging." Ships use radar to help "see" other ships, buoys, shorelines, etc. Beacons sometimes provide distinctive targets. Radar is used in aircraft navigation (see Doppler-radar), in positioning, and in remote sensing.

RADIO FREQUENCY - A frequency above 3kHz. Radio frequencies are subdivided into bands.

RAYLEIGH WAVE - A seismic wave propagated along the free surface of a semi-infinite medium. The particle motion near the surface is elliptical and retrograde, in the vertical plane containing the direction of propagation.

RAYPATH - A line everywhere perpendicular to wavefronts (in isotropic media). The path which a seismic wave takes.

REFLECTION SURVEY - A survey of geologic structure using measurements made of arrival time of events attributed to seismic waves which have been reflected from interfaces where the acoustic impedance changes.

RESOLUTION - The ability to separate two features which are very close together.

SEISMIC AMPLIFIER - An electronic device used to increase the electrical amplitude of a seismic signal. (See geophone)

SEISMIC CAMERA - A recording oscillograph used to produce a visible pattern of electrical signals to make a seismic record.

SEISMIC VELOCITY - The rate of propagation of a seismic wave through a medium.

SEISMOGRAM - A seismic record.

SHEAR WAVE - A body wave in which the particle motion is perpendicular to the direction of propagation. (Same as S-wave, equivoluminal, transverse wave).

SHOOTER - The qualified, licensed individual (powderman) in charge of all shotpoint operations and explosives handling on a seismic crew.

SHOT DEPTH - The distance down the hole from the surface to the explosive charge, often measured with loading poles. With small charges the shot depth is measured to the center or bottom of the charge, but with large charges the distances to both the top and bottom of the column of explosives are usually given.

SHOT INSTANT - (Time Break [TB], Zero Time) - The time at which a shot is detonated.

SHOTPOINT - Point of location of the energy source used in generating a particular seismogram. Expressed either sequentially for a line (i.e. SP 3) or in engineering notation (i.e. SP 3+00).

SIGNAL ENHANCEMENT - A hardware development utilized in seismographs and resistivity systems to improve signal-to-noise ratio by real-time adding (stacking) successive waveforms from the same source point and thereby discriminating against random noise.

SIGNAL-TO-NOISE RATIO SOUNDING- The energy (or sometimes amplitude) divided by all remaining energy (noise) at the time; abbreviated S/N.

SOLE FAULT - A low-angle thrust fault forming the base of a thrust sheet; also, the basal main fault of an imbrication.

SOUNDING - Measuring a property as a function of depth; a depth probe or expander. Especially a series of electrical resistivity readings made with successively greater electrode spacing while maintaining one point in the array fixed, thus giving resistivity-versus-depth information (assuming horizontal layering); electric drilling, probing, VES (vertical electric sounding).

SPREAD - The layout of geophone groups from which data from a single shot are recorded simultaneously.

STONELEY

WAVE - A type of seismic wave propagated along an interface.

SURFACE WAVE - Energy which travels along or near the surface (ground roll).

SYNTHETIC SEISMOGRAM - An Artificial seismic record manufactured from velocity log data used to compare with and actual seismogram to aid in identify events or in predicting how stratigraphic variations might affect seismic record. Often constructed from sonic log data alone although density data may also be incorporated.

TAKEOUT - A connection point to a multiconductor cable where geophones can be connected.

THRUST FAULT - A fault with a dip of 45 degrees or less over much of its extent, on which the hanging wall appears to have moved upward relative to the footwall. Horizontal compression rather than vertical displacement is its characteristic feature.

TIME BREAK (TB)- The mark on a seismic record which indicates the shot instant or the time at which the seismic wave was generated.

TIME DOMAIN - 1. Expression of a variable as a function of time, as opposed to its expression as a function of frequency (frequency domain). Processing can be done using time as the variable, i.e., "in the time domain". For example, convolving involves taking values at successive time intervals, multiplying by appropriate constants, and recombining; this is equivalent to filtering through frequency-selective circuitry. It is also equivalent to Fourier transforming, multiplying the amplitude spectra, and adding the phase spectra ("in the frequency domain"), and then inverse-Fourier transforming.

2. Time-domain induced polarization is called the pulse method (q.v.)

TOMOGRAPHY - The reconstruction of an object from a set of its projections. Tomographic techniques are utilized in medical physics as well as in cross-borehole electromagnetic and seismic transmission surveys.

TRACE - A record of one seismic channel. This channel may contain one or more geophones. A trace is made by a galvanometer.

UPHOLE METHOD- Also called the Meissner technique, a method of reconstructing wave front diagrams by shooting at several depths and recording on a full surface spread of geophones. Derived wavefront diagrams yield a true picture of wavepaths and, therefore, layering in the subsurface.

WAVE TRAIN - (1) The sum of a series of propagating wave fronts emanating from a single source. (2) The complex wave form observed in a seismogram obtained from an explosive source.

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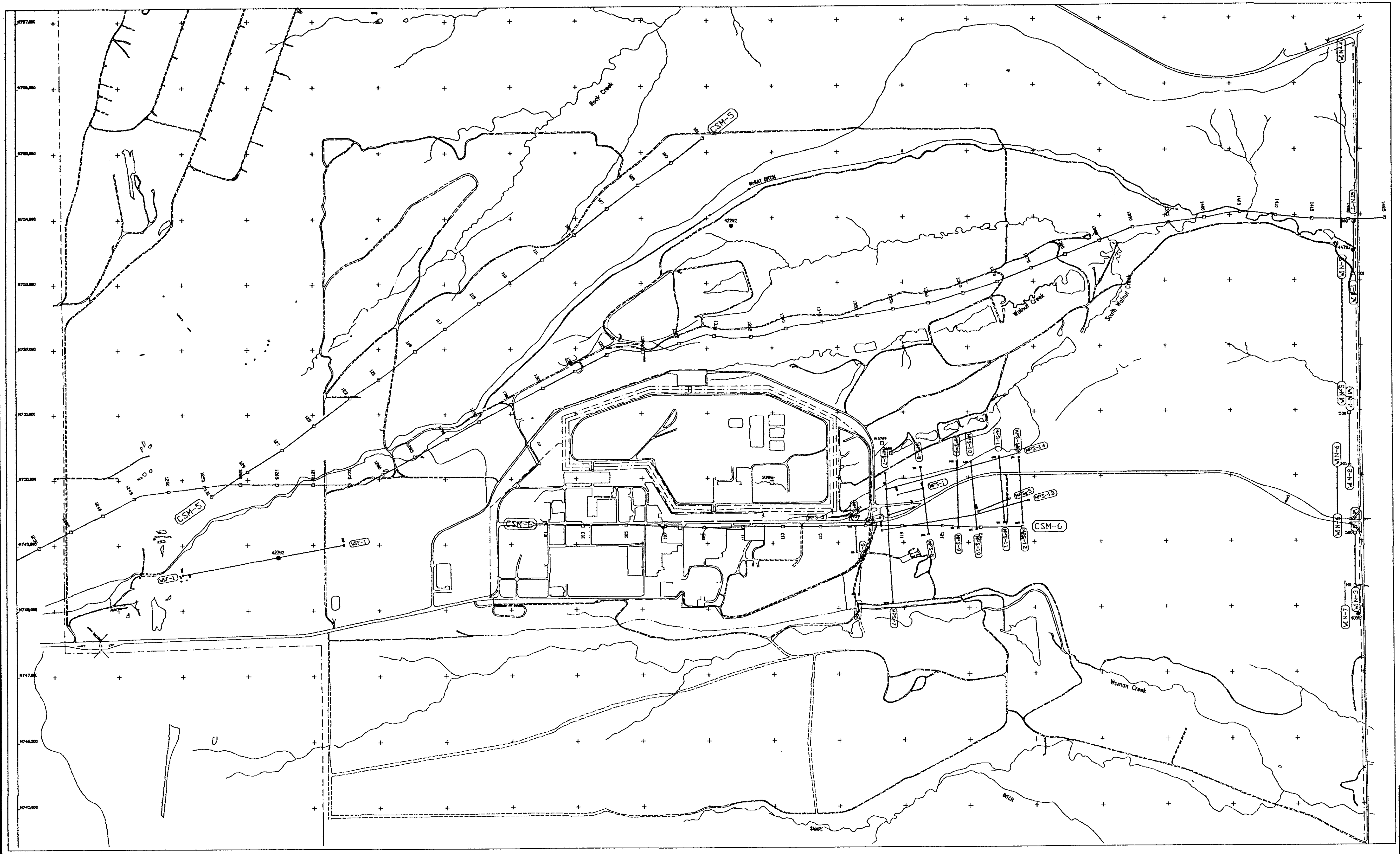
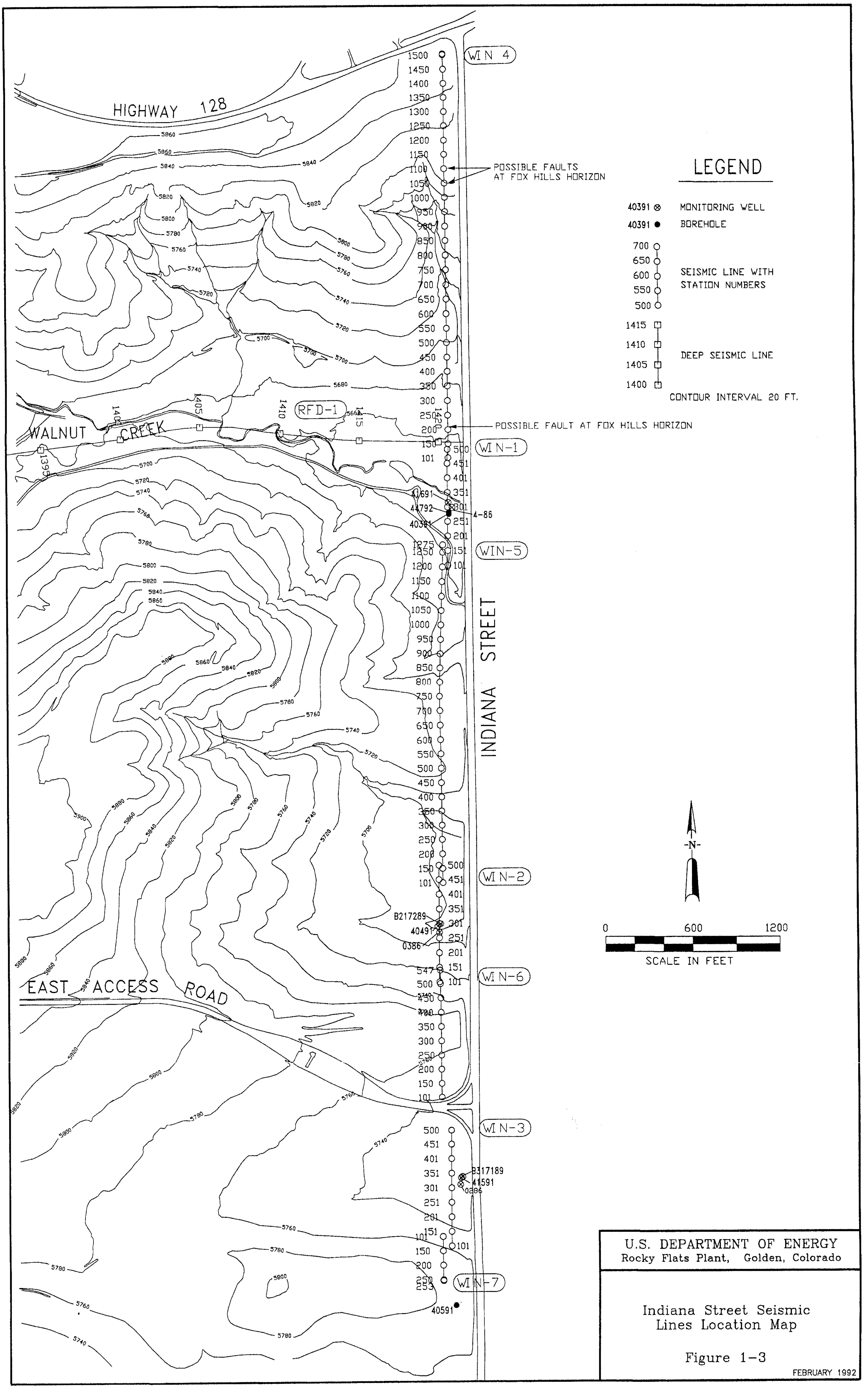


U.S. DEPARTMENT OF ENERGY
Rocky Flats Plant, Golden, Colorado

Location of Seismic Coverage and Vertical Seismic Profiles at Rocky Flats Plant

Figure 1–2

September 1993



U.S. DEPARTMENT OF ENERGY
Rocky Flats Plant, Golden, Colorado

Indiana Street Seismic Lines Location Map

Figure 1-3

FEBRUARY 1992

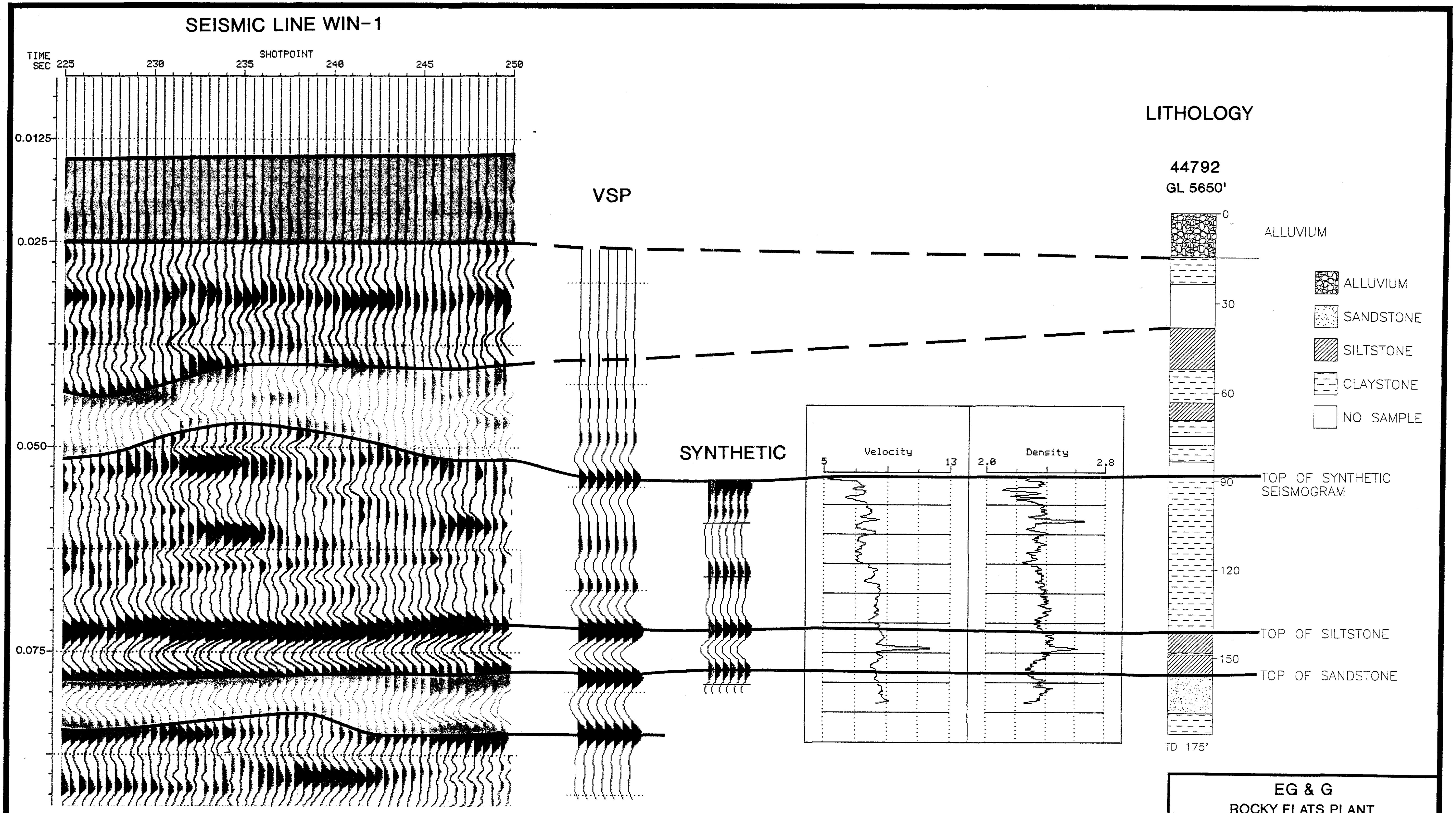


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FIGURE 4-1
COMPOSITE DISPLAY
CORRELATING BOREHOLE
44792 TO LINE WIN-1

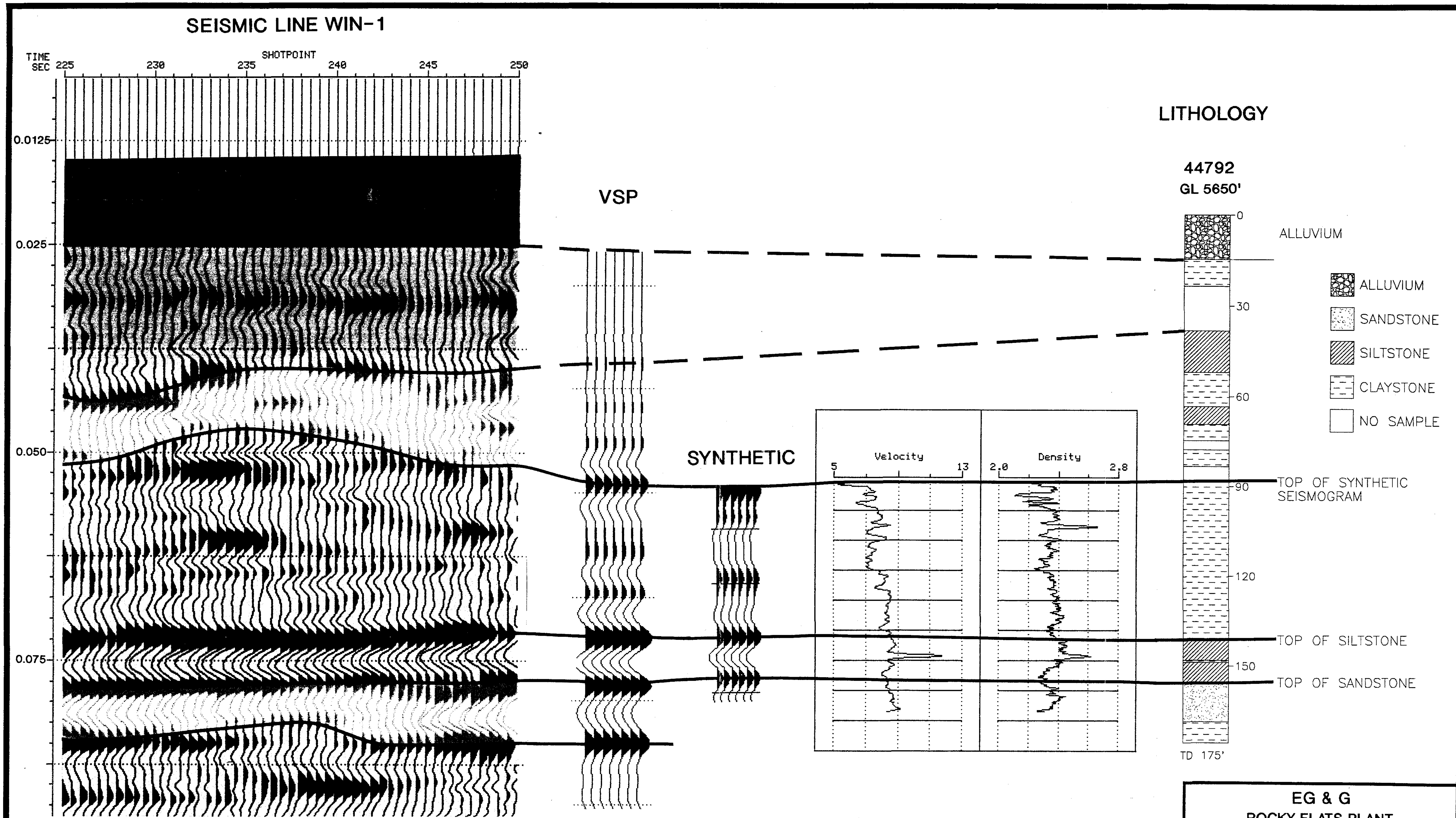

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FIGURE IV-6
COMPOSITE DISPLAY
CORRELATING BOREHOLE
44792 TO LINE WIN-1

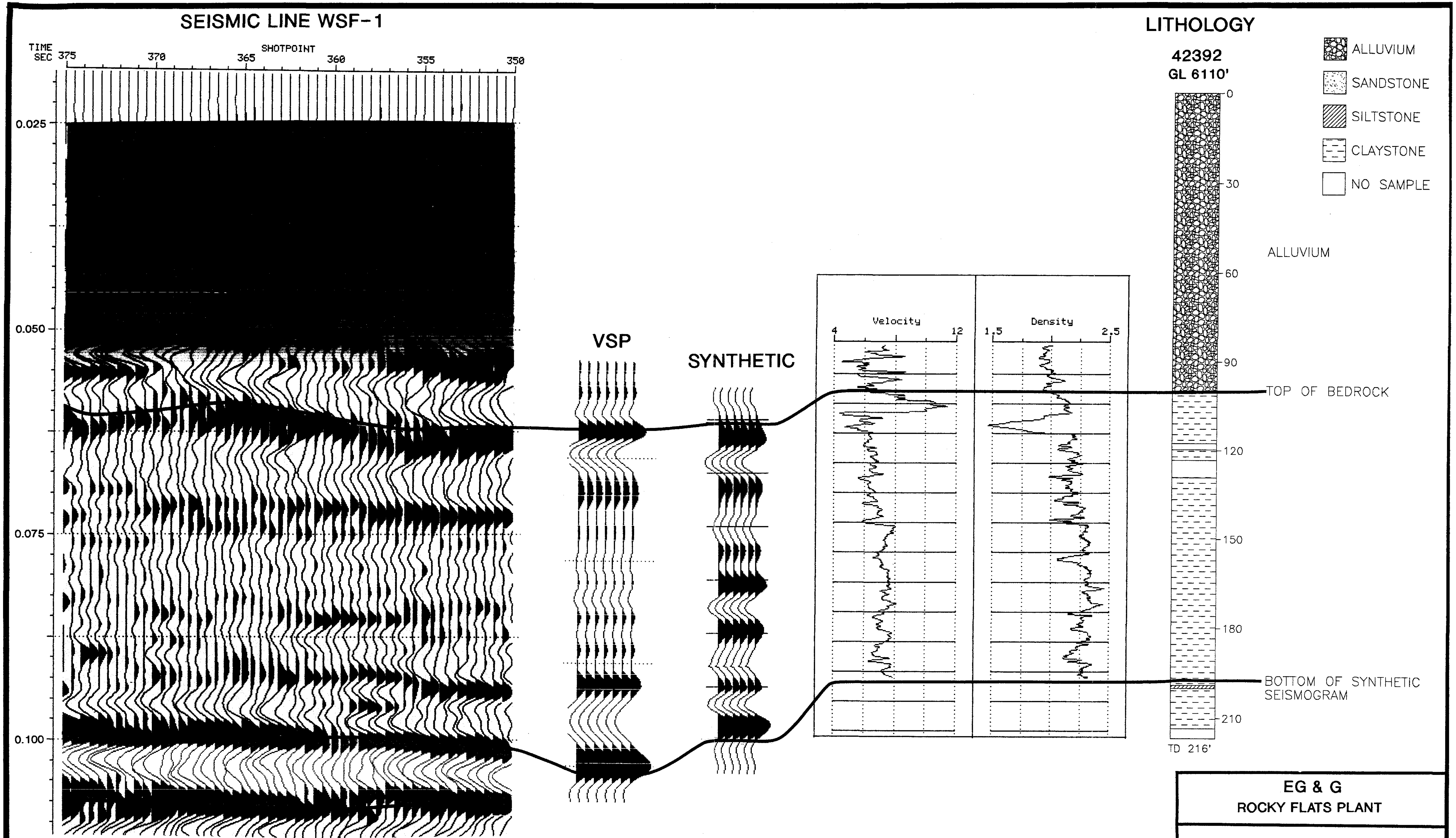

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FIGURE IV-11
COMPOSITE DISPLAY
CORRELATING BOREHOLE
42392 TO LINE WSF-1

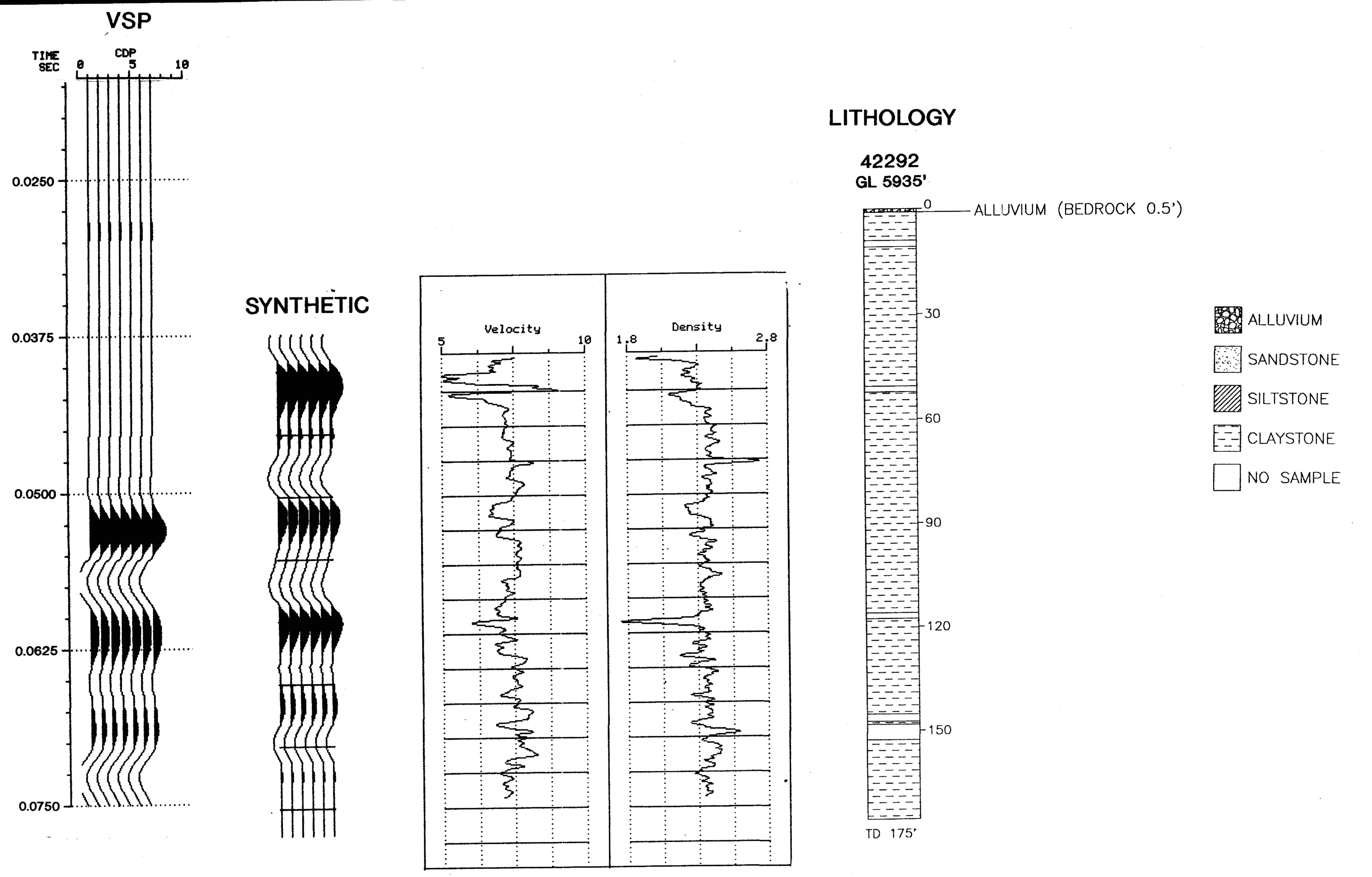

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FIGURE IV-16

COMPOSITE DISPLAY
FOR BOREHOLE 42292

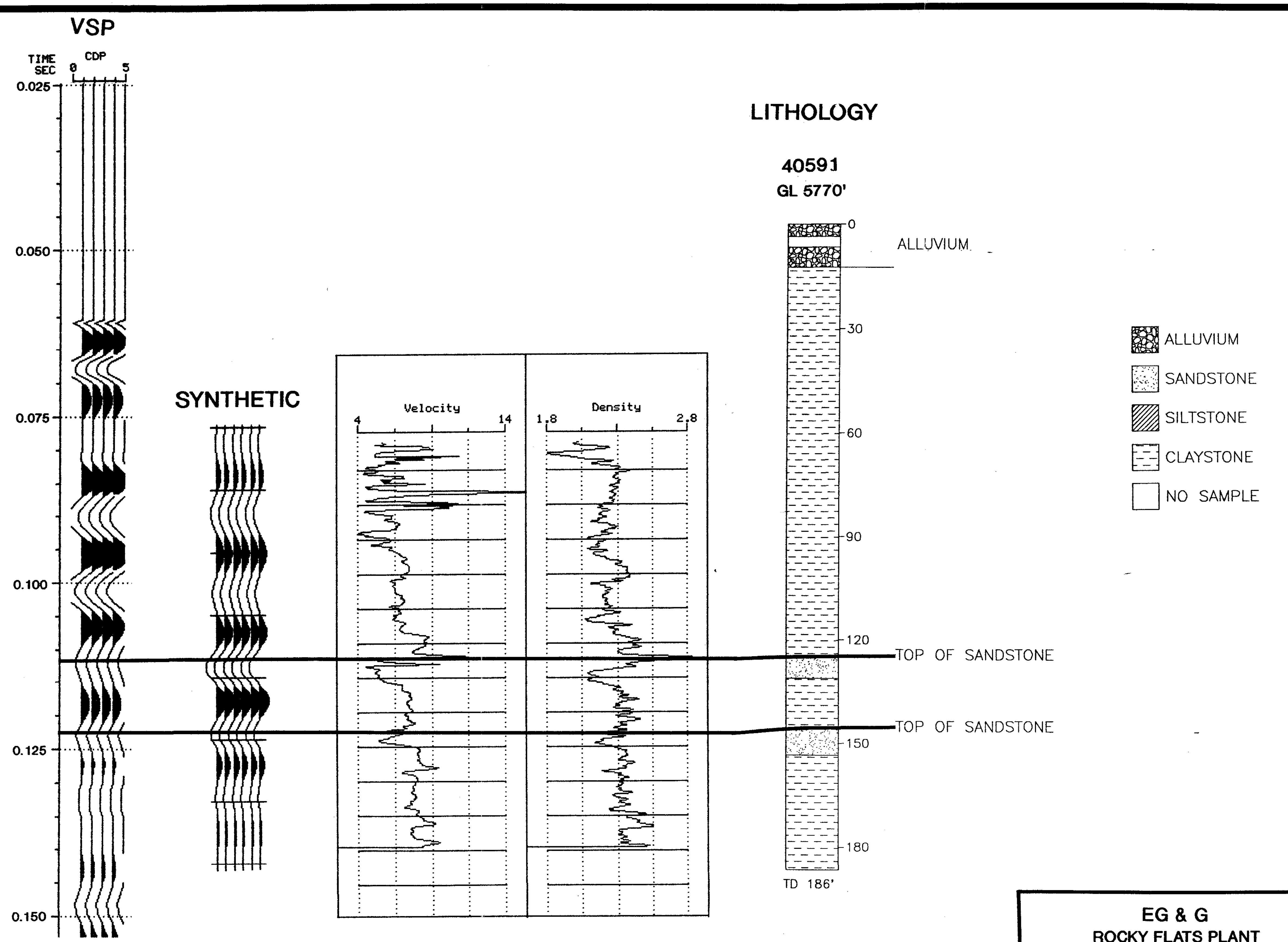

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FIGURE IV-21

COMPOSITE DISPLAY FOR BOREHOLE 40591

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FIGURE 4-5

COMPLEX TRACE ATTRIBUTE DISPLAY-INSTANTANEOUS FREQUENCY LINE WIN-5

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FIGURE 4-2

COMPLEX TRACE ATTRIBUTE DISPLAY-INSTANTANEOUS PHASE LINE WIN-4

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FIGURE 4-4

COMPLEX TRACE ATTRIBUTE DISPLAY-INSTANTANEOUS PHASE LINE WIN-5

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FIGURE 4-3

COMPLEX TRACE ATTRIBUTE DISPLAY-INSTANTANEOUS FREQUENCY LINE WIN-4

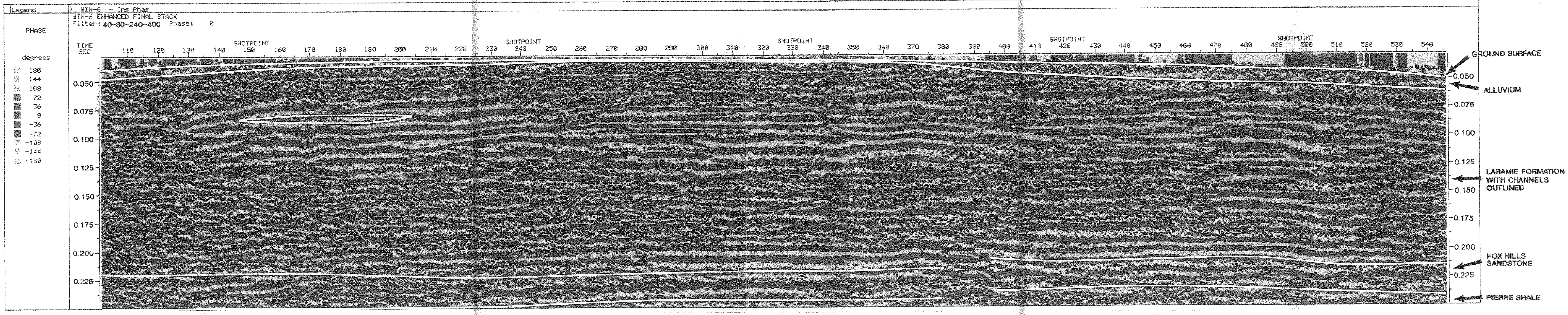

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FIGURE 4-6

COMPLEX TRACE ATTRIBUTE DISPLAY-INSTANTANEOUS PHASE LINE WIN-6

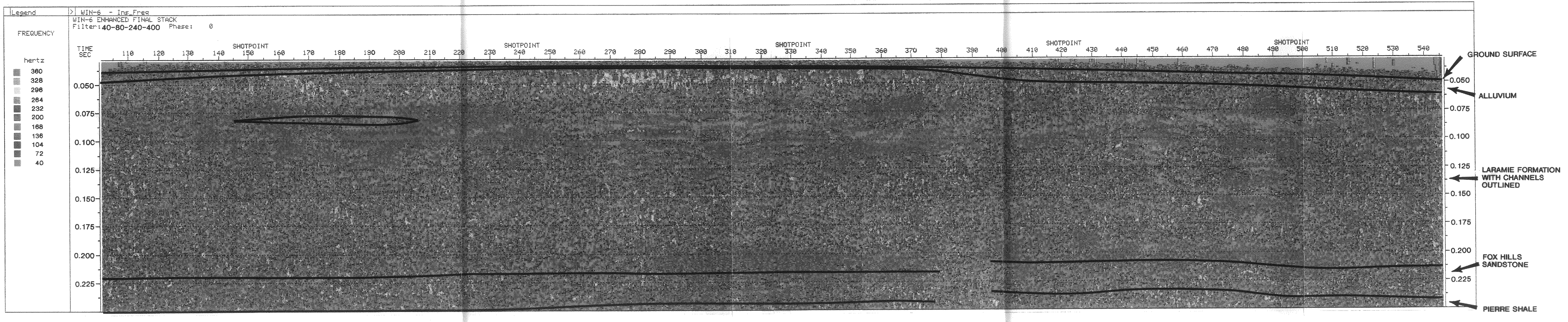

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FIGURE 4-7

COMPLEX TRACE ATTRIBUTE DISPLAY-INSTANTANEOUS FREQUENCY LINE WIN-6

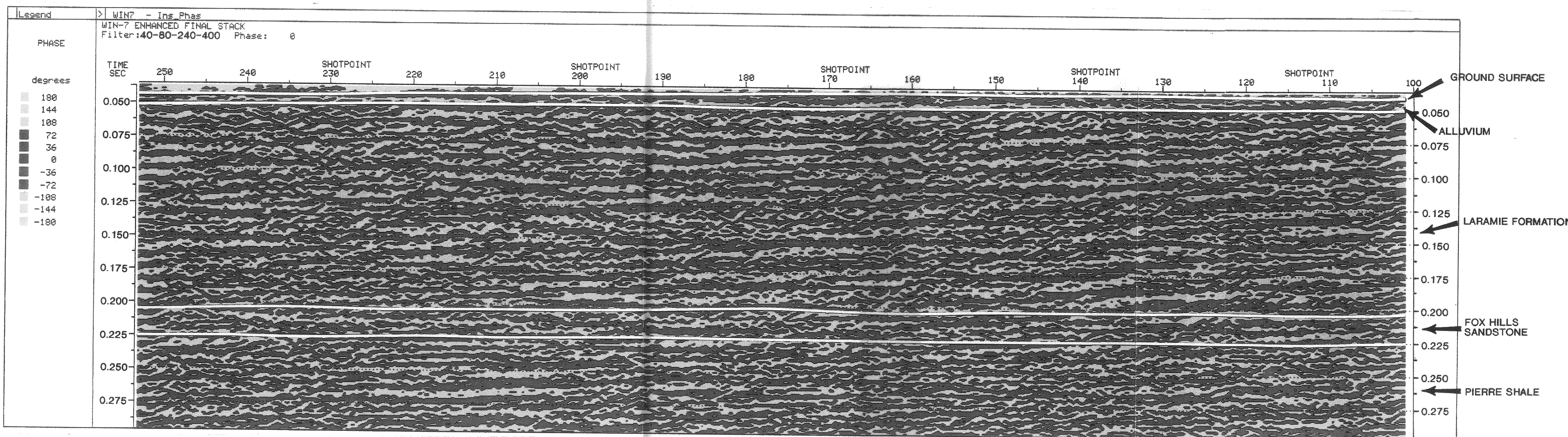

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FIGURE 4-8
COMPLEX TRACE ATTRIBUTE DISPLAY-INSTANTANEOUS PHASE LINE WIN-7

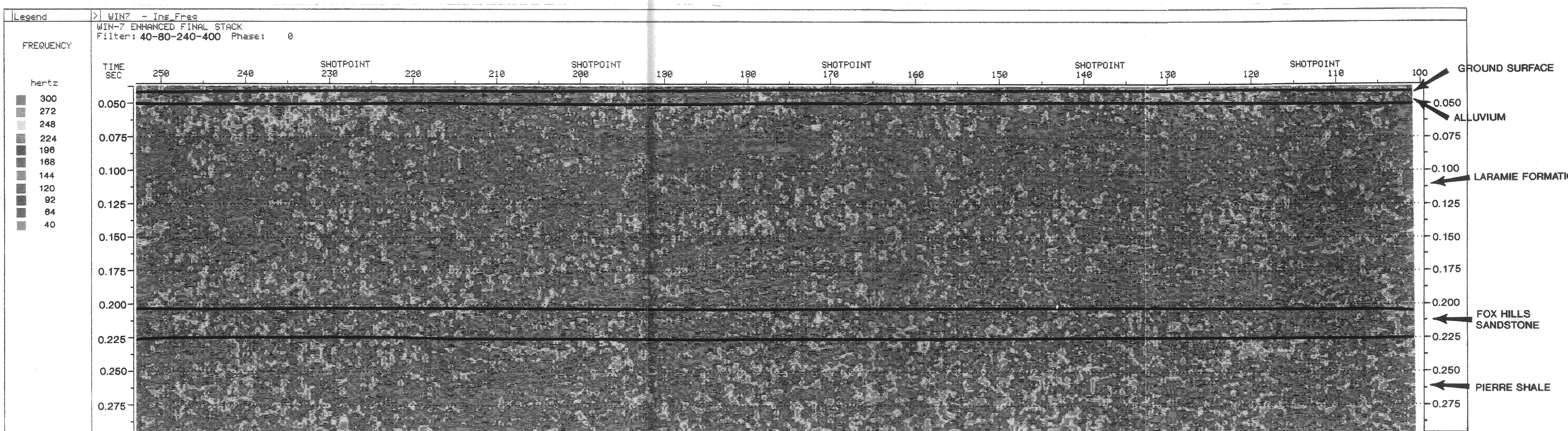

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FIGURE 4-9

COMPLEX TRACE ATTRIBUTE DISPLAY-INSTANTANEOUS FREQUENCY LINE WIN-7